NITROGEN MOVEMENT, RETENTION AND UPTAKE IN THE CORN (*ZEA MAYS* L.) ROOT ZONE AS INFLUENCED BY CULTIVATION AND WATER MANAGEMENT

By

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This dissertation is dedicated to my father, the late
Manduba Reuben Wajingomtuwa Katete Saka; my uncle,
the late Sokalikalimba Aaron Malijanga Khumba Ndhlovu;
and my mother,
Phelire Mirriam Wapelera NyaNdhlovu.

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An irrigated corn field experiment was conducted during the 1983 season at Gainesville, Florida, to investigate the dynamics of nitrogen and water in the root zone as well as corn growth, N uptake and yields as influenced by cultivation, water and fertilizer management. The experimental design consisted of a combination of three water treatments (rainfed, water stress at tasseling and optimum irrigation) and two cultivation methods (conventional and subsoiling) to give six main plots, each of which was split for two levels of fertilizer N (168 and 413 kg N ha^{-1}). Soil samples were collected in 15-cm increments up to the 105 cm depth throughout the growing season to characterize the storage of water and N in the root zone. Cumulative uptake and distribution of N in various plant parts and dry matter accumulation were also monitored by periodic sampling.

A two-week water stress imposed during the reproductive growth stages resulted in about 50% reduction in grain yields when compared

with the optimum irrigation treatment. A similar two-week stress period under low N fertility conditions resulted in about 30% reduction in grain yields, illustrating the interactive effects of water and N. Cumulative N uptake at harvest ranged from 176 to 266 kg N ha^{-1}. Periodic water and/or N stresses during the season led to decreased plant N uptake in the reproductive water stress and rainfed treatments.

Subsoiling did not influence the soil-water and N stored in the root zone or cumulative plant N uptake during the season. This was attributed to the ineffectiveness of the subsoiling and a favorable rainfall distribution during the growing season.

Within a given subplot, concentrations of NO_3^--N and NH_4^+-N in the soil profile were highly variable, particularly in the surface soil layers (0-15 and 15-30 cm). The observed variation was attributed to non-uniform (banded) fertilizer N application and the inability to locate and sample on the fertilizer band. Computation of the integral amounts of N in the root zone reduced some of this variability and facilitated comparison of the treatment effects. In contrast to the soil samples, variability in N content in the plant samples was low.

Cumulative N uptake, location of NO_3^--N pulses, and soil-water storage in the root zone simulated by the NITROSIM model were in close agreement with the measured data. The leaching of NH_4^+-N and NO_3^-N, and N uptake by corn under rainfed conditions on a typical Malawi soil were simulated by NITROSIM. These simulations were used to evaluate fertilizer N split applications to optimize crop use.

CHAPTER 1

INTRODUCTION

Nitrogen and water are the most important variables for crop and fiber production in present-day agricultural systems. The numerous desirable and undesirable effects of these variables (deficiency, sufficiency and/or excess) on plant growth, crop yields and the environment are well documented in agricultural, environmental and engineering journals. Nonetheless, the multiplicity of interacting factors and processes that influence their dynamics under field conditions are still not very well understood. This has caused an upsurge of interest in the study of nitrogen and water dynamics under field conditions.

Because nitrogen is found in limited quantities, large amounts of this nutrient element are annually applied to crop lands to increase yields (Keeney, 1982). The intensive use of these inorganic nitrogen fertilizers, together with improved crop varieties and sound soil and water management techniques, has contributed significantly to the current celebrated "green revolution." However, it has also been recognized that nitrogen contributes to groundwater pollution and is a threat to the environment (Nielsen et al., 1982; Watts and Hanks, 1978).

Conventionally, nitrogen has been applied to increase crop yields. Water has been applied to increase crop yields and/or leach excess salts in the root zone. This resulted in research programs that were aimed at determining total amounts of water and nitrogen that produced maximum (or optimum) yields as illustrated in various reviews in agronomic journals (e.g., Nelson, 1956; Maynard et al., 1976). These efforts have defined the criteria for quantifying nitrogen and/or water sufficiency and/or deficiency. The limitations of these approaches have recently been reviewed by Greenwood (1976) and Hanks et al. (1983). Most of the early research findings revealed that the final yield is a function of a multiplicity of factors and processes although little effort was made to study them simultaneously.

The realization that nitrogen is a threat to the environment and groundwater aquifers has cast some doubts on the credibility of the traditional soil, water and nitrogen management programs which only aimed at maximizing the final grain yield.

At present, there are limited data on the mobility of agricultural chemicals under field situations. It is further realized that little work has been done on detailed coordinated systems of management for soil-water and nutrients that take into account, simultaneously and sequentially, the effects of interacting factors and processes that determine the fate (mobility, retention, uptake and transformation) of these chemicals and the final yields of grain and dry matter.

The situation has further been aggravated by the fact that the transient nitrogen-water-plant system is very complex. Any attempt to study the various variables simultaneously and sequentially is a formidable task that is difficult to accomplish. The recent development of high speed computers has, however, accelerated the development of simulation models that take into account the effects of various factors and processes. Field application of these models will greatly increase our understanding of the complex mechanisms and processes that determine the fate of these agrochemicals.

In view of these facts, it is clear that there is a continuing need to develop more efficient agricultural systems from limited and diminishing soil resources in which soil, water and nutrients are managed in such a way that nutrient use efficiency is maximized and loss to groundwater aquifers is minimized. Such systems will optimize grain yields and increase returns to the farmer and reduce nutrient leaching beyond the rooting zone.

The work reported in this dissertation is intended to be a contribution to a systematic study of nitrogen and water dynamics using simulation models and a corn field experiment. The specific objectives of this study were to

(i) determine the fate (leaching, retention, uptake and transformations) of inorganic nitrogen species in the corn root zone under different cultivation and water management practices,

(ii) determine the effects of nitrogen and water stress on corn growth and grain yield,

(iii) evaluate the forecasting ability of NITROSIM -- a nitrogen simulation model by comparing simulated and experimental data for a Florida soil and climatic condition, and

(iv) simulate N uptake and transport in selected Malawi soils using the NITROSIM model.

CHAPTER 2

LITERATURE REVIEW

Nitrogen in Crop Production and the Environment

Nitrogen is the most important nutrient element that has the greatest impact on crop and fiber production. It is a major nutrient element that is required and utilized in large quantities by all plants. The current trend is that its use will be greatly increased in the coming decades. In a recent review on nitrogen behavior in agricultural soils, Keeney (1982) cites the work of Chancellor and Ross (1976) who estimate that food production must increase by 88% in the year 2000 in order to match food production with world population growth. A population of between 6 and 7 billion is estimated for the year 2000. An earlier estimate by Smith (1963) indicated that world population is doubling every 35 years. With these large increase in world population, increased food production on limited land area and resources will require increased inputs of inorganic nitrogeneous fertilizers.

In recent years, it has been observed that nitrogen could have serious detrimental effects on humans and animals (Watts and Hanks, 1978; Keeney, 1982; and Nielsen et al., 1982, 1983). Nitrogen has been recognized to contribute significantly to groundwater pollution and to affect the ozone layer that protects humans from ultraviolet radiation. Wild and Cameron (1979) and Maynard et al. (1976), among others, have reported up to two thousand cases of death as being caused by nitrate pollution in Europe and the United States. The United States Public Health Service has set a maximum of 10 mg N L^{-1} in potable water.

Nitrogen excess in plants has been reported to induce toxic effects (Court et al., 1962). The undesirable effects of nitrogen deficiency on corn growth are stunted size, delayed silking and barren cobs resulting in greatly decreased grain yields (Robins and Domingo, 1953).

Influence of Nitrogen and Water on Crop Growth and Yields

The availability and mobility of nitrogen in the root zone is highly influenced by water. There are numerous interactions between water and nitrogen that affect crop growth and the final grain yield in various ways.

Research findings over the past four or five decades which have been reported in agronomic journals have clearly demonstrated that if little amounts of these variables, either singly or in combination, are not available to the plant, tremendous reductions in yield occur. In some cases total crop failure has been observed. On the other hand when they are supplied in sufficient amounts, high yields are realized. The effects of nitrogen and water stress on the functioning of plant parts and their quantitative measurement will be the topic of the ensuing subsections.

Water Stress

Soil water stress during the different growth stages has been observed to be one of the main causes of decreased grain yields, *cetaris paribus*. Robins and Domingo (1953), Wilson (1968), Bauder et al. (1975), Strulter et al. (1981), Stegman et al. (1980) and Harder et al.

(1982), among many others, have shown that soil water stress during the reproductive stages is the main cause of decreased yields. They have, however, demonstrated that corn plants are tolerant to small durations of droughts during the vegetative stages. Similar observations have recently been reported by Bennett and Hammond (1983). In an effort to systematically identify growth limiting factors that determine final crop yield, Archer et al. (1982) have demonstrated that limited supply of any growth factor at any stage of crop development limits the attainment of potential yield.

Limited supply of water reduces (i) nutrient supply to plant roots, (ii) nutrient uptake by plant roots, (iii) water use, and (iv) nutrient translocation and assimilation in the plant. Perhaps the only advantage of limited water supply in the crop root zone is reduced nutrient (or pollutant) migration to groundwater aquifers.

Nitrogen Stress

Nitrogen plays an important role in crop nutrition. It is found as a component of the chlorophyll molecule, amino acids and enzymes. Nitrogen is also important in the utilization of carbohydrates and the stimulation of root development. Nitrogen also influences the uptake of other nutrients like phosphorus and potassium. Thus, nitrogen stress would retard the functioning of many plant parts resulting in greatly reduced crop yields.

The light green color and/or yellowing of plant leaves is a symptom of nitrogen deficiency. Nitrogen sufficiency is reflected in the development of dark green leaves.

Quantifying Nitrogen and Water Stress

Water stress or deficit has been defined in terms of the physical status of water in the plant. Parameters like total water potential or turgor potential have been used to measure water stress. On the other hand, nitrogen deficiency has conventionally been defined in terms of the plants response to added nutrient.

In the last two decades, concern has been expressed over the inadequancy of this definition of nutrient (nitrogen) deficiency. To remedy this, Greenwood et al. (1965) opted for a quantitative definition of nitrogen stress in crop plants. They have defined the degree of nitrogen stress, S_N, as a quantitative estimate of the intensity of current nitrogen deficiency in a plant which can be evaluated as the proportion by which the growth rate of the plant falls short of the maximum growth rate attained with non-limiting supply of nitrogen over the period when stress is being measured. In recently published work on cereals and grasses, symptoms of nitrogen stress have been observed to show up when $S_{NR} = 40\%$ (or $S_{NC} = 60\%$) (Halse et al., 1969; Power, 1971), where S_{NR} and S_{NC} are the degrees of nitrogen stress based on relative growth rate and growth rate respectively.

In his recent review, Greenwood (1976) suggests the use of the following parameters to quantify stress: (i) leaf nitrogen, (ii) dry weight, (iii) leaf elongation, (iv) leaf area and (v) carbon dioxide exchange rate. Halse et al. (1969) used dry weight to quantify stress in wheat plants. Power (1971) also used dry weight to quantify nitrogen and water stress in a sward of bromograss in North Dakota. Recently, Mutti (1984) has used relative dry weight to measure nitrogen stress in corn plants.

While the quantification of nitrogen stress is a conceptually pleasing phenomenon, it has some serious practical limitations. It does not tell the farmer how much nitrogen to apply to correct for the deficiency. As Greenwood (1976) points out, perhaps this is the price that one has to pay for avoiding crop response curves. The same is true if water stress is quantified using these principles.

At the present moment, the use of both Greenwood et al. (1965) concept and the conventional crop response curves will continue to be used hand in hand until better nitrogen water management systems are formulated that take into account all input factors and processes that control and determine final crop yield.

Influence of Water on Nitrogen Leaching

Various physical, chemical and biological processes and factors (which interact simultaneously) influence the fate of applied nitrogen in various ways in cropped land areas. In the soil-plant-atmosphere system, nitrogen can be dissipated in numerous ways, including denitrification, volatilization, adsorption/desorption, microbiological transformations, plant root uptake or leaching to groundwater.

In the absence of plant uptake, migration to groundwater through the convective stream of water (rainfall or irrigation) seems to be the main sink for nitrogen. Field studies by Watts and Hanks (1978), Watts and Martin (1981) and Martin et al. (1982) have clearly demonstrated that one of the main causes of nitrogen deficiency in excessively irrigated plots is nitrogen leaching beyond the corn root zone.

Studies on the transport of agricultural chemicals both under laboratory and field conditions by various investigators

(Balasubramanian et al., 1973; Burns, 1974, 1975; Burns, 1976; Graetz et al., 1973; Saffigna et al., 1977; Chichester and Smith, 1978; Starr et al., 1974) have clearly shown that water is the main transporter of applied chemicals in soils. Hence, careful supply of water to crop lands is an important agricultural practice that has to be addressed seriously by agriculturalists and environmentalists. Increased crop production depends on efficient crop use of water and nitrogen. This in turn reduces chemical mobility to groundwater aquifers.

Influence of Cultivation on Crop Growth, Yields, Water and Nitrogen

Soil cultivation is necessary to (i) prepare a good seedbed, (ii) kill weeds, and (iii) loosen compacted soil layers. In most cases it is used to perform a combination of the above functions. Here, we are concerned with the third aspect: loosening compacted subsoil layers for increased root development and increased utilization of both soil-water and nutrients.

The effects of subsoiling on soil-water, nutrients and yields have been a subject of many investigations. A recent review article by Reicosky (1983) gives the current state-of-the-art on this subject. Robertson et al. (1957) have reported increased crop yields from subsoiling and deep placement of fertilizers and lime in a variety of Florida soil types. The effect of subsoiling was more pronounced when soil-water stress conditions occurred during the early part of the growing season. Campbell et al. (1974), working on millet in the southeastern United States, found that chiseling reduced the strength of root restricting layers, increased rooting depth and increased the final grain yield. They concluded that whether or not beneficial effects of chiseling can be observed depended on the duration of the drought as well as on the soil's physical properties that affect root development. Reicosky et al. (1976) chiseled some corn plots to a depth of 38cm. They subjected corn to stressed and non-stressed soil-water conditions. They found that chiseled plots yielded significantly more than shallow tilled plots when subjected to limiting soil-water conditions. This led them to conclude that under sufficient soil-water conditions chiseling was of no consequence, while under limited soil-water conditions chiseling increased crop yields. These findings were confirmed more recently by Rhoads (1978).

Some investigators reported no significant benefit from subsoiling even under conditions of limiting soil-water conditions. Rios and Pearson (1974) found no significant grain yield difference between deep plowed and shallow plowed plots. They attributed this lack of response to high levels of soluble aluminum in the subsoil. Al toxicity, caused by high levels of acidity, has been reported to inhibit root development. Reicosky (1983) quotes from the work of Parker and coworkers conducted in Georgia in the late sixties who reported no significant yield response due to deeper nematode penetration in subsoiled plots under optimum soil-water conditions. This is probably due to increased porosity and increased infiltration rates. Under such situations root development has been impaired, restricting soil-water and nutrient extraction in the root zone of deep tilled plots. This, in part, has resulted in erroneous conclusions regarding the effects of subsoiling.

While deep tillage allows for better root development under ideal soil, water and nutrient conditions, it enhances rapid leaching of soluble nutrients beyond the root zone. Under uncontrolled soil-water conditions (rainfall) nutrient loss due to leaching might contribute significantly to the observed decreased grain yield. Under controlled soil-water conditions (e.g., irrigration), soil-water and soluble nutrients can be applied as frequently as possible to meet the crops requirements.

Thus, it can be concluded that to increase crop use efficiency of water and nutrients, improved nutrient and water management systems must be developed. This is the topic of the next subsection.

Methods of Maximizing Nitrogen Use Efficiency and Minimizing Losses

Many interacting and interrelated processes and factors affect the final grain yield. To optimize crop production a means of minimizing N losses and maximizing N use efficiency must be devised. The options for achieving these goals are numerous and varied. Generally, four broad categories can be distinguished.

The first option is the use of efficient or best management agricultural practices. Here emphasis is on soil and water conservation, crop rotations or use of cover crops. The second option considers the application of limited amounts of N to croplands. This, however, might have the undesirable effects of reducing N use efficiency. The third option is the use of improved management of water and nutrient systems. This is concerned with the timing, rate and quantity of N and water applications that meets the crops requirements and reduces their transport beyond the root zone. The fourth option is a fundamental change in agriculture itself. This includes innovations in breeding crop plants that have the ability to fix atmospheric N, or legumes that have a higher capacity to fix atmospheric N. Our main concern here is the third option.

The soils and climate of the humid southeastern United States provide a unique challenge and opportunity to corn production compared to those in traditional corn growing areas of the Midwest. Most parts of the southeastern U.S. are dominated by well drained, deep sandy soils that are characterized by low water and nutrient holding capacities. Although the total annual rainfall is adequate for rainfed agriculture, its distribution pattern during the growing season is poor, erratic and unpredictable (Hammond et al., 1981). The occurrence of one or two weeks of drought has damaging effects on corn growth and yields. Thus, water has for a long time been recognized as one of the main factors that limit corn production in Florida.

In the late fifties, tillage and/or naturally occurring pans in subsurface horizons were identified as another obstacle to the attainment of high yields. Thus, research programs in Florida were directed at combating these undesirable effects of water stress and root restricting pans. Robertson and coworkers (1957, 1958, 1959) carried out a series of experiments aimed at studying the effects of deep plowing and deep placement of fertilizers. Concurrent with these studies were efforts directed at obtaining fertlizer response curves for various crops. Rhoads (1981) quotes from the Crop Reporting Board of Florida published in 1980, which reports average corn yields of 1,000 kg ha^{-1} in 1951 and 3,100 kg ha^{-1} in 1979. Thus, although water, tillage pans and nutrients were identified as the main independent variables in the yield equation, response curves, subsoiling and deep placement of fertilizers only provided a small fraction of the answer. A system of management for soil-water and nutrients that ensured the availability of water and nutrients at all times during the growing season was therefore required. The concepts of controlled water application to meet the atmospheric evaporative demand and crops requirement coupled with a limited supply of soluble nutrients to meet the crops requirements only (Phene and Beale, 1976) were found to be suitable for Gainesville conditions (Mansell et al., 1977, Hammond et al., 1981). The strategy has been to apply high frequency irrigation that supplies small quantities of water and soluble nutrients to a limited portion of the root zone. This is equivalent to the concept of "planned deficit irrigation" that leaves room for rain in the root zone as used by Watts and Hanks (1978) on Nebraska sandy soils. Similarly, Rhoads and Stanley (1981) and Rhoads (1981) have introduced the "plow layer" water management and fertilization program concept. This concept has resulted in corn grain yields increasing from 3,100 kg ha^{-1} in 1979 to the present high yields of up to 12,500 kg ha^{-1} under Florida conditions (Rhoads, 1981).

Various current research programs on water and nutrient management in Florida are utilizing the Rhoads and Stanley (1981) concepts to arrive at various prediction regression equations. Hammond et al. (1981) developed production functions for corn, while Riestra-Diaz (1984) concentrated on production functions for corn, soybeans, carrots and sweet potatoes. Obreza (1983) reported on the nutritional requirements of high-yield irrigated crop production systems. Mutti (1984) examined the effects of water and nitrogen stress on corn growth and grain yields. He imposed nitrogen and soil-water stress during the vegetative growth stages (between 50 and 66 days after corn emergence). Bennett and Hammond (1983) have reported on the effects of vegetative water stress on corn growth and grain yields.

These studies, and others which have not been cited here, have provided us with a wealth of useful information. The regression equations from these studies can be used for forecasting purposes. However, it is clear that there is room to extend the scope of the above studies to fully utilize the concepts embedded in "plow layer" water management and program fertilization. Firstly, it is noted that the regression equations derived from these studies are site-specific and should be used with caution when applied to other sites. Secondly, the above studies did not take into account the transport, retention and microbiological transformations of N in the soil-water-plant system. As such, additional studies are required to fully characterize the fate of applied agrochemicals in cropped land areas, especially in those areas where efforts to maximize grain yields are as important as to minimize groundwater pollution. The present studies were designed to characterize nitrogen dynamics both in the soil and in the plant under vegetative nitrogen stress and reproductive soil-water stress, while Mutti (1984) characterized nitrogen dynamics in the plant under conditions of nitrogen and soil-water stress during the vegetative growth stages. This is of particular importance to Florida where droughty conditions (which reduce grain yields) are punctuated by unpredictable heavy rain storms (which leach soluble nutrients and other agrochemicals to groundwater aquifers). Thus, there is a need for a systematic study of process oriented coordinated systems of management for soil, water and nutrients that integrate all the input variables that determine crop growth and the final yield. In a recent review on irrigation management and crop production related to nitrate movement, Hanks et al. (1983) advocate the use of such management systems which are capable of predicting the consequences of applied nutrients and water that take into account all production variables.

Such an approach is not site specific and will provide an opportunity for agrotechnology transfer from one environment to other environments. Because of the utility that can be gained from such systems of management, the rest of this review chapter will be devoted to the quantitative description of nitrogen transport, retention, transformations and plant uptake using mathematical models.

Mathematical Models for Describing Nitrogen Dynamics in Soils

Schlicher (1905) is perhaps the first person to have observed differential movement of solutes and water in the soil. Earlier, Lawes and coworkers (1881) discovered that solutes and water moved at greater velocities in larger pores than in smaller pore domains. These early observations have provided the stimulus and impetus on which present day theories and concepts pertinent to solute and water transport in porous media are based.

Two types of theories have been advanced in the study of solute and water transport: (i) chromatographic and (ii) miscible displacement. In the first theory, the flow domain is partioned into either (i) discrete units (Martin and Synge, 1941) or (ii) treated as a continuous plate unit (Glueckauf, 1955). The experimental work of Rible and Davis (1955), among others, demonstrated the applicability of this theory in explaining the distribution of adsorbed and solution phase solutes during flow. However, the theory was not able to explain the mixing that takes place due to pore water velocity distributions in pore domains. This is one of the primary reasons that stimulated engineers and agricultural scientists to develop the more comprehensive miscible displacement theory (Lapidus and Amundson, 1952, Schedigger, 1960; Nielsen and Biggar, 1961, 1962). An excellent treatise on this subject is given by Bear (1979). Davidson et al. (1983) have detailed the current approaches to modeling the physical processes of diffusion, mechanical dispersion and the dispersion term caused by the diffusive transfer of solutes between the mobile and immobile pore domains. Selim and Iskander (1981), Tilloston and Wagenet (1982), Tanji (1982) and Rao and Jessup (1982) have detailed modeling approaches applicable to the chemical and microbiological processes of ion-exchange (adsorption/desorption) transformations and degradation.

In the ensuing subsection, mathematical models developed from the miscible displacement theory will be presented to illustrate (i) the advances that have been made over the last three decades, and (ii) the associated limitations to field application of these models. In the next subsection, the current approaches in the development and use of simple management oriented models developed from miscible displacement theory and the chromatographic theory will be presented.

Comprehensive (Research Oriented) Mathematical Models for Describing Solute Flow

Soil-water transport. By combining the equation of continuity and the Darcy equation, the partial differential equation for describing one-dimensional transient water flow in unsaturated soil profiles in the presence of transpiring plants can be written as (Feddes et al., 1978)

$$C(h)\frac{\partial h}{\partial t} = \frac{\partial}{\partial z}(K(h)(\frac{\partial h}{\partial z} - 1)) - W(z,\theta,t) \qquad (2\text{-}1)$$

where θ = volumetric soil-water content, $cm^3\ cm^{-3}$

z = vertical distance, positive downwards, cm

h = soil-water pressure head, cm

$K(h)$ = soil hydraulic conductivity as a function of soil-water pressure head, h; $cm\ hr^{-1}$

t = time, hr

$C(h)$ = differential water capacity, cm^{-1}

q = Darcy soil-water flux, $cm^3\ cm^{-2}\ hr^{-1}$

H = total soil-water pressure head, cm.

W = volume of water taken up by roots per unit soil volume per unit time, $cm^3\ cm^{-2}\ hr^{-1}$

There are generally two approaches to modeling the water uptake term, $W(z,\theta,t)$. The first is a microscopic approach, where a single root is considered as a sink term (Hillel et al., 1975, Nye and Tinker, 1977). The second is a macroscopic approach, where the whole root system is treated as a sink term (Nimah and Hanks, 1973a,b; Molz and Remson, 1970, 1971; Feddes et al., 1978).

Numerical as well as analytical solutions have been obtained for the nonlinear partial differential equation (2-1). To obtain numerical solutions, equation (2-1) is approximated by an algebraic finite-difference approximation (Ames, 1977; Carnahan et al., 1969; Remson et al., 1971). Hillel et al. (1975), Selim et al. (1977b), Klute and Heermann (1978), Watts and Hanks (1978) and Tillotson and Wagenet (1982) have used explicit-implicit schemes to solve equation (2-1). A comparison of several numerical methods (without the plant extraction term) has been presented by Haverkemp et al. (1977), while a compendium of recent work on soil-water dynamics is given by Hillel (1977).

The numerical solutions have proved very useful in predicting soil-water contents in space and time. As it will be discussed later, this is probably because soil-water content is a "capacity" parameter that is normally distributed.

Solute (Nitrogen) transport. Using similar principles of conservation of mass and momentum, the partial differential equation for describing the one-dimensional convective-dispersive-diffusive transport of inorganic nitrogen species including adsorption/desorption, sink source effects and plant uptake can be written as (Davidson et al., 1978)

$$\frac{\partial}{\partial t}(\theta C_i + \rho S_i) = \frac{\partial}{\partial z}\left(D_h \theta \frac{\partial C_i}{\partial z} - qC_i\right) - \sum_{i=1}^{n} \Phi_i \qquad (2\text{-}2)$$

where C_i = solution concentration of the ith N species, mg cm^{-3}

q = soil-water flux, cm^3 cm^2 hr^{-1}

ρ = soil bulk density, g cm^{-3}

S_i = adsorbed phase solute of the ith N species, mg g^{-1}

Φ_i = sink/source term of the ith N species accounting for transformations and uptake, cm^3 cm^{-2} hr^{-1}

$D_h = D_m(\theta) + D_e(v) + D_s(\phi, r \ldots)$, is the hydrodynamic dispersion coefficient, cm^2 hr^{-1}

$D_m(\theta)$ = effective molecular diffusion coefficient, cm^2 hr^{-1}

$D_e(v)$ = mechanical dispersion coefficient, cm^2 hr^{-1}

$D_s(\phi, r...)$ = dispersion term accounting for the diffusive transfer between mobile and immobile phases, cm^2hr^{-1}

ϕ = fraction of pore water residing in the conducting pore domains

r = radius of immobile pore domains, cm, and

V = average pore-water velocity

Rao and Jessup (1982b) have given a comprehensive list of equilibrium kinetic and degradation models that have been used by different researchers to describe the adsorption/desorption term, $\frac{\partial(\partial S_i)}{\partial t}$. For instantaneous reversible equilibrium conditions (Fig. 2-1), the linear Freudlich adsorption equation is applicable as follows:

$$S = K_D C \qquad (2\text{-}3)$$

$$\frac{\partial S}{\partial t} = K_D \frac{\partial C}{\partial t} \qquad (2\text{-}4)$$

where K_D = adsorption coefficient ($cm^3\ g^{-1}$). Substituting equation (2-4) into (2-2), we get

$$\frac{\partial}{\partial t}(\theta C_i + \rho K_D C_i) = \frac{\partial}{\partial z}(D_h \theta \frac{\partial C_i}{\partial z} - qC_i) - \sum_{i=1}^{n} \Phi_i \qquad (2\text{-}5a)$$

or

$$(\theta + \rho K_D)\frac{\partial C_i}{\partial t} + C_i \frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}(D_h \theta \frac{\partial C_i}{\partial z} - qC_i) - \sum_{i=1}^{n} \Phi_i \qquad (2\text{-}5b)$$

There are many microbiological tranformations that take place in the soil after nitrogen (NH_4NO_3) application (Fig. 2-1). In most cases, first-order rate equations have been assumed to adequately describe these transformations (Cho, 1970; Rao et al., 1975; Wagenet et al., 1977, Davidson et al., 1978). If we further assume that (i) there is negligible organic matter in the soil, as is the case in most of Florida's sandy soils ($k_3=k_4=k_5=0$), and (ii) the denitrification process

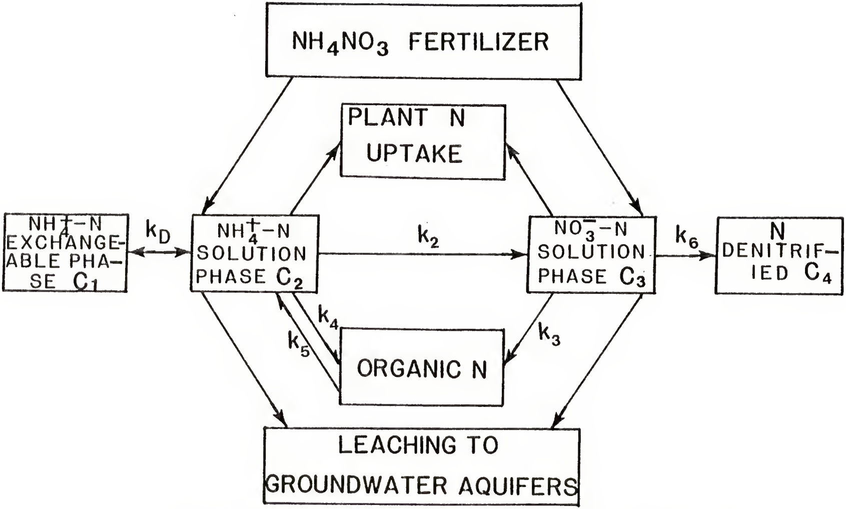

NH_4NO_3 FERTILIZER
PLANT N UPTAKE
NH_4^+–N EXCHANGEABLE PHASE C_1
k_D
NH_4^+–N SOLUTION PHASE C_2
k_2
NO_3^-–N SOLUTION PHASE C_3
k_6
N DENITRIFIED C_4
k_4
k_5
ORGANIC N
k_3
LEACHING TO GROUNDWATER AQUIFERS

Fig. 2-1 Schematic Representation of Nitrogen Transformations, Ion Exchange, Uptake and Leaching

is negligibly small (k_6=0), as the case is with deep well-drained homogeneous soil profiles, then first order rate equations for NH_4^+-N and NO_3^--N can be written as follows:

$$\frac{\partial}{\partial t}(NH_4^+\text{-}N) = \frac{\partial C_2}{\partial t} = -k_2 \theta C_2 \qquad (2\text{-}6)$$

$$\frac{\partial}{\partial t}(NO_3^-\text{-}N) = \frac{\partial C_3}{\partial t} = -k_2 \theta C_3 \qquad (2\text{-}7)$$

where k_2 is the first order rate coefficient for nitrification (day^{-1}) and is assumed to be invariant with depth; C_2 and C_3 are NH_4^+-N and NO_3^--N solution concentrations ($mg\ cm^{-3}$), respectively. However, many researchers (Olsen and Kemper, 1968; McLaren, 1971; Stanford and Smith, 1972; Stanford and Epstein, 1974) have reported that rate coefficients are a function of environmental factors such as pH, temperature, soil-water content, etc. Modeling efforts of Tillotson and Wagenet (1982) and Hagin and Amberger (1974) have included some of these factors at different levels of detail.

Thus, the simultaneous transport and transformation equations for NH_4^+-N and NO_3^--N , including plant uptake, can be written as

$$\frac{\partial}{\partial t}(\theta C_2 + \rho K_D C_2) = \frac{\partial}{\partial z}(D_h \theta \frac{\partial C_2}{\partial z} - qC_2) - k_2 \theta C_2 - U_2 \qquad (2\text{-}8)$$

$$\frac{\partial}{\partial t}(\theta C_3) = \frac{\partial}{\partial z}(D_h \theta \frac{\partial C_3}{\partial z} - qC_3) - k_2 \theta C_3 - U_3 \qquad (2\text{-}9)$$

where U_2 and U_3 are nitrogen uptake terms for NH_4^+-N and NO_3^--N, respectively.

The two approaches used in modeling soil-water extraction apply equally for nitrogen (NH_4^+-N and NO_3^--N) uptake terms U_2 and U_3. This will be discussed in detail in the next sub-section.

Since equation (2-2) is nonlinear, it can be solved by numerical methods only. Bresler (1973), Davidson et al. (1978), Tanji et al. (1981), and Selim and Iskander (1981) have used explicit-implicit procedures to obtain solutions to this equation using constant depth and time increments. Tillotson and Wagenet (1982) have modified the scheme of Bresler (1973) to include variable depth increments.

For simpler cases, when steady state conditions are assumed to prevail, as is the case with laboratory soil columns, analytical solutions have been obtained (Cho, 1971, Misra et al., 1974; Wagenet et al., 1977). Selim and Mansell (1977), Van Genuchten (1981) and Freeze and Cheery (1979) have derived analytical solutions for the solute transport equation in soils. A comprehensive list of currently available analytical solutions for solute transport models in porous media have been given by Van Genuchten and Alves (1982).

Initial and boundary conditions. Equations (2-1) and (2-2) will yield unique solutions only when appropriate initial and boundary conditions are specified. Three types of boundary conditions can be specified (Feddes et al., 1978; Ames, 1977). The first is called the Dirichlet condition. This condition specifies the independent variable. The second is the Neumann condition. This specifies the derivative of the dependent variable. The third type is called the mixed condition and is a mixture of the first two types. The initial condition is chosen to describe the state variables of the system before it is activated.

The following boundary and initial conditions have been specified by many investigators when studying the transport of solutes in porous media

$$h = h_0 \quad , \quad z \geq 0,\ t = 0 \qquad \text{(2-10a)}$$

$$q = -K(h)\left(\frac{\partial h}{\partial z} - 1\right) \quad , \quad z = 0,\ t < 0 \qquad \text{(2-10b)}$$

$$C_2 = C_{20} \quad , \quad z \geq 0,\ t = 0 \qquad \text{(2-10c)}$$

$$C_3 = C_{30} \quad , \quad z \geq 0,\ t = 0 \qquad \text{(2-10d)}$$

$$qC_{2s} = D_h\theta\frac{\partial C_2}{\partial z} + qC_2 \quad , \quad z = 0,\ t < T \qquad \text{(2-10e)}$$

$$qC_{3s} = Dh\theta\frac{\partial C_3}{\partial z} + qC_3 \quad , \quad z = 0,\ t < T \qquad (2\text{-}10f)$$

$$0 = D_h\theta\frac{\partial C_2}{\partial z} + qC_2 \quad , \quad z = 0,\ t > T \qquad (2\text{-}10g)$$

$$0 = D_h\theta\frac{\partial C_2}{\partial z} + qC_3 \quad , \quad z = 0,\ t > T \qquad (2\text{-}10h)$$

$$h = h_d \quad , \quad z = L,\ t \geq 0 \qquad (2\text{-}10i)$$

where C_{20} = a constant initial NH_4^+-N concentration in the soil profile, mg cm^{-3}.

C_{30} = a constant initial NO_3^--N concentration in the soil profile, mg cm^{-3}.

C_{2s} = concentration of NH_4^+-N in applied fertilizer, mg cm^{-3}

C_{3s} = concentration of NO_3^--N in applied fertlizer, mg cm^{-3}.

T = specified time for fertilizer (solution or water) application.

The other terms are as defined before. These conditions specify the following:

(i) uniform soil profile with respect to soil-water pressure head and nutrient concentrations.

(ii) solutions having concentrations of C_{2s} and C_{3s} are applied at the soil surface for time period T.

(iii) flux boundary conditions are specified at the soil surface for both water and solute during the time period T.

(iv) a constant soil-water pressure head is specified at the bottom of the root zone.

The mechanistic nitrogen model presented here (equations (2-1), (2-8), (2-9) and (2-10)) has several desirable attributes in that it includes the major processes and factors that govern the fate of nitrogen in agricultural soils. This model can be used to monitor, control and forecast or predict the leaching of nitrogen beyond the crop root zone to groundwater, retention in the soil profile, transformations that take place in the soil and the amount that is taken up by plant roots.

Computer simulations using the above model (together with appropriate boundary and initial conditions) have been carried out by several investigators (Bresler, 1973; Hagin and Amberger, 1974; Rao et al., 1975; Davidson et al., 1978; Tanji and Gupta, 1978; Watts and Hanks, 1978; Frissel and Van Veen, 1981; Selim and Iskander, 1981; Iskander and Selim, 1981; Tillotson and Wagenet, 1982). Some (e.g., Watts and Hanks, 1978, Tillotson and Wagenet, 1982) have observed good agreement between simulated and field measured values. However, in most cases simulated results have not matched field data precisely. Most of these investigators (e.g. see Bresler, 1980; Rao et al., 1982; Nielsen et al., 1982, 1983) have attributed this failure to several factors among which are

(i) poor choice of mathematical models that do not precisely describe the physical system,

(ii) improper specification of boundary conditions,

(iii) poor stability, consistency and convergence characteristics of the resulting algebraic equations,

(iv) the unavailability of necessary input data for both soil and plant parameters,

(v) the input parameters have been assumed to be deterministic in nature, while most investigators are of the opinion that they are better treated as stochastic in nature,

(vi) even when assumed to be deterministic, as the case has been in most modeling efforts, the methods for measuring these parameters are at present inadequate, time consuming and expensive; this has led researchers to use laboratory determined values, which are often found to be three or four magnitude smaller compared to field values, and

(vii) the physical, chemical and biological parameters have been observed to vary both in space and time.

Spatial soil variability seems to be the main limiting factor in verifying simulation models. This will now be discussed in more detail.

Soil spatial variability. Many investigators have recently started addressing the problem of soil spatial variability or soil heterogeneity in connection with solute transport in agricultural soils. Nielsen et al. (1973), Wagenet and Rao (1983) and Warrick and Nielsen (1980), among others, have demonstrated that soil physical parameters vary both spatially and temporally.

Flow-related parameters or "intensity" factors (e.g., $K(h)$), $D(\theta)$ and $v(= q/\theta)$ have been observed to be log-normally distributed, while "capacity" factors (e.g., ρ and θ) have been shown to be normally distributed. This means that to get a representative mean value of a parameter such as $K(h)$, a large number of samples is required. On the other hand, fewer samples are required to estimate parameters such as θ. This, perhaps, partially explains why better results have been obtained in predicting soil-water content using simulation models.

The failure of the comprehensive models to accurately monitor, predict, or forecast nutrient mobility partly seems to lie in the modelers inability to accurately measure the input parameters to the same degree of accuracy or scale of observation. Nielsen et al. (1982, 1983) give convincing evidence why model predictions have failed to accurately match observed field data. They start by re-examining the concept of the representative elementary volume, REV, (Bear, 1972, 1979) to argue that transport equations are sometimes conceptually incorrect. The parameters, ρ, K_D, θ, q and D, are seldom measured at the same scale. Exact and correct measurements of these parameters require the identification of a REV and defining similar scales of observation that exist simultaneously.

Parameters like D (a microspic term) and q (a macroscopic term) have seldom been used in the same transport equation even if they were not detrmined at the same level of observation or without first identifying a REV. Hydraulic conductivity is usually calculated from the value of $\partial H/\partial z$ and q, with the implicit assumption that q and $\partial H/\partial z$ pertain to the same size spatial domain. The value of K_D is determined experimentally from the values of S and C, which are assumed to pertain to the same size spatial domain. Finally, it should be recognized that the value of the convective flux term, qC, will be conceptually correct if q and C are measured at the same level of observation and careful identification of a REV.

However, more often than not, the above parameters have implicitly been assumed to pertain to the same spatial domain when applied in transport equations. The uncertainty attached to the input parameters has far reaching consequences on the output results. The question to be raised is: if $K(\theta)$ in Darcy's Law is of uncertain value, how do we expect to calculate q with a high level of accuracy? Further, if q is in error, how do we expect to predict convective flux, qC, with a reasonable degree of accuracy? To this end, the heterogeneity and complexity of field soils defies our ability in verifying solute transport models.

Nonetheless, attempts have been made to solve this problem. Concepts utilizing geostatistical analysis (correlograms, variograms and spectral density functions), reviewed and appraised by Nielsen et al. (1982, 1983), are receiving wide use application in characterizing spatial variability. In other instances, soil parameters have been scaled using principles of similar media advocated by Miller and Miller (1956). Warrick and Amoozegar-Fard (1979), Warrick et al. (1977), Simmons et al. (1979), Wagenet and Rao (1983) and Rao et al. (1983a) have used scaling techniques.

Thus it can be concluded that spatial variability, coupled with differing spatial scales at which the parameters are measured, impairs the usefulness and forecasting ability of these mathematical models. And this probably explains why many researchers, not realizing under what conditions and circumstances their parameters were determined and valid, have erroneously concluded that their models were at fault or in error.

The failure of the deterministic models has led many investigators to look at alternative modeling approaches. We can distinguish five such approaches. In the first approach, the use of more comprehensive models is sought. This will require modeling the various factors and processes at the same level of detail and conceptual completeness, taking into account a REV applicable to each parameter and appropriate scales of observation. In the second approach, stochastic models are used. The input parameters into these statistical models are determined by the laws of probability and not determined independently in the field or by curve fitting procedures. Smith and Schwartz (1980) have applied stochastic differential equations along these lines. Rao et al. (1981) have used a stochastic approach to model convective-dispersive solute flow in saturated soils. The third approach is the use of stochastic parameters into deterministic models. Recent modeling efforts by Bresler and Dagan (1979) fall in this category. The fourth approach is the use of transfer function models. This is also a class of stochastic formulations (Nielsen et al., 1983). Jury (1975, 1982, 1983), Raats (1980, 1983) and Mansell (1983) have applied this modeling approach to estimate travel times of solutes in soil profiles. The fifth approach is the use of simplified mathematical models. The more comprehensive models are simplified by neglecting some terms (usually the dispersive-diffusive term). Emphasis is on characterizing gross solute behavior over large spatial and temporal scales (e.g., Frere et al., 1975; Rao et al., 1977; Rose et al., 1980, 1981, 1982).

Thus, it can be concluded that even though the comprehensive mathematical models are conceptually pleasing in that they include all the factors and processes that dictate solute behavior in soils, their usefulness is still restricted to laboratory soil columns. They are valuable research tools especially in identifying the more important processes and factors and in sensitivity analysis studies. The latter is important in identifying those parameters that are more sensitive to small perturbations in the systems behavior.

Since this work is intended to characterize N under field conditions (a large spatial domain) over the entire growing season (a large temporal scale), simplified models will be used.

Simplified Mathematical Models for Describing Solute (Nitrogen) Dynamics in Agricultural Soils

In their analysis of model development and verification, Rao and Jessup (1982) emphasized that soil spatial variability is the main limiting factor to model verification under field conditions. In a earlier communication, Rao et al. (1982) detailed the criteria for model use and selection. From their analysis, it is apparent that simplified models (i) may provide fairly accurate answers for field application, (ii) are much less expensive compared to comprehensive (research oriented) models (e.g., Davidson et al., 1978; Frissel and Van Veen, 1981; Selim and Iskander, 1981) and (iii) do not require huge computational facilities and can adequately be handled by field managers without constant advice from competent computer programmers. Thus, it is not surprising that many investigators are presently developing or verifying these simplified, management oriented, models (e.g., Towner, 1982; Smith et al., 1984).

Terkeloub and Babcock (1971) and Burns (1974, 1975) working independently developed simplified solute leaching models based on the chromatographic theory. An applied solute was assumed to mix with the soil solution already in each compartment as it moved down the soil profile. Solute transport was controlled by input water, field capacity value, θ_{fc}, and wilting point percentage value, θ_{15}. Addiscott (1977) extended the conceptualization of this kind of approach to include aggregated soils. Recently, Moscardini (1981) verified the applicability of the Burns model on field data obtained at Rothamsted. Towner (1982) has provided an analytical solution to the convective flow equation (by neglecting the effects of diffusion and dispersion) which he found to be applicable and equivalent to the Burns model. With appropriate simplications, he has been able to show that the model of Burns is actually a special case of his more general finite difference approximation to the convective solute flow equation.

Rose et al. (1980, 1981, 1982), Dayananda et al. (1980), De Smedt and Wierenga (1978), Frere et al. (1975) and Davidson et al. (1978) have obtained simplifed models by neglecting the diffusive-dispersive term in the transport equation (2-1). Bresler (1980), realizing the practical significance and importance of simplified models for field application, neglected the convective-dispersive term and applied simple mass balance concepts to characterize the fate of solutes in soils. This type of fluid flow (neglecting the diffusive-dispersive term) approximates that of piston displacement.

There is also another class of simplified mathematical models which are chromatographic in nature but are based on systems analysis concepts. De Laat (1980) and Rao et al. (1981) have used the above approach to describe water and solute transport in agricultural soils.

In this study, the simplified Piston Displacement Model (PDM) (Rao et al., 1977; Davidson et al., 1978) for estimating solute front locations in homogeneous soil profiles will be presented. The use of simplified models is justified under Florida (Gainesville) conditions because of the occurrence of deep, well-drained homogeneous sandy soils. The low water and nutrient holding capacities of these soils provide an excellent opportunity for locating solute fronts in an otherwise solute free medium. The concepts of high frequency irrigation and multiple N applications, as discussed in the previous sections, are all conducive to N characterization under Florida conditions.

Mathematical analysis of the PDM. Let us consider the transport of a conservative solute (such as Cl^-) under conditions where the diffusive-dispersive term is negligible. Then a θ based equation for the soil-water flow equation (Eq. (2-1)), can be written as

$$\frac{\partial \theta}{\partial t} = -\frac{\partial q}{\partial z} - W \tag{2-11}$$

and the solute flow equation (Eq. (2-2)) can be written as

$$\frac{\partial(\theta C)}{\partial t} = -\frac{\partial(qC)}{\partial z} \tag{2-12a}$$

or

$$C\frac{\partial \theta}{\partial t} + \theta\frac{\partial C}{\partial t} = -q\frac{\partial C}{\partial z} - C\frac{\partial q}{\partial z} \tag{2-12b}$$

Substituting equation (2-11) into (2-12), we get

$$\theta\frac{\partial C}{\partial t} = CW - q\frac{\partial C}{\partial z} \tag{2-13}$$

Two cases can be considered: (i) an infiltration event (including the subsequent redistribution phase) and (ii) an evaporation event. For the first case, $\partial q/\partial z >> W$, so that W can be neglected.

Hence equation (2-13) reduces to

$$\theta\frac{\partial C}{\partial t} = q\frac{\partial C}{\partial z} \tag{2-14}$$

Since C is a function of both space and time, i.e., $C = C(z,t)$, it follows from the chain rule that

$$dC/dz = \partial C/\partial z + \partial C/\partial t)(dt/dz) \tag{2-15}$$

At the depth of maximum solute penetration, $dC/dz = 0$, so that equation (2-15) becomes

$$\frac{dz_{zf}}{dt} = -\frac{\partial C/\partial t}{\partial C/\partial z_{sf}} \tag{2-16}$$

where z_{sf} is the maximum solute peak depth (i.e., $z = z_{sf}$). From equation (2-14), $q/\theta = -\frac{\partial C/\partial z}{\partial C/\partial z_{sf}}$, $z = z_{sf}$, so that equation (2-16) reduces to

$$\frac{dz_{sf}}{dt} = (q/\theta)_{z_{sf}} \tag{2-17}$$

Since the diffusive-dispersive term has been ignored, the infiltration event is essentially a pulse of solute flow, so that q can be taken as a delta function of θ (Rose et al., 1980). This modeling approach is therefore based on two assumptions. The first is that soil-water initially present in the soil profile is completely displaced ahead of the water entering at the soil surface (i.e., there is no mixing). The second is that the soil-water residing in all pore sequences participates in the flow process (i.e., valid for soils that are not aggregated where one usually conceptualizes mobile and immobile soil-water).

By integrating equation (2-17), we can obtain an expression for the maximum solute peak as follows:

$$\int_0^{z_{sf}} dz = \int_0^{\Delta t} (q/\theta)_{z_{sf}} dt$$

or $$z_{sf} = (q/\theta)\Delta t \qquad (2\text{-}18a)$$

If we assume a homogeneous soil profile so that during the redistribution period θ drains to θ_{fc} (i.e., $\lim_{t \to T_{rd}} \theta = \theta_{fc}$), where T_{rd} is the resistribution period (usually assumed to be between 2 to 6 days for most field soils), then we can simplify equation (2-18a) to equation (2-18b).

$$z_{sf} = (qT_{rd})/\theta_{fc} = I/\theta_{fc} \qquad (2\text{-}18b)$$

where $I = qT_{rd}$ = the amount of total water that infiltrated into the soil.

The second case is the evaporation event where $W >> \partial q/\partial z$, i.e., $q = 0$, so that from equation (2-13) it follows that

$$\theta \frac{\partial C}{\partial t} = CW \qquad (2\text{-}19)$$

indicating that the water withdrawal process (without plant solute extraction) will tend to increase solute concentration. However, the solute peak remains the same which is our main interest here. Experimentally, it should equally be observed that even under conditions of nutrient uptake, the solute front location should remain the same. The view taken here is that plant nutrient extraction is uniformly distributed over the whole soil volume exposed to plant roots.

Equation (2-18) has been derived for non-adsorbed solutes that are assumed to move along with the convective stream of water in an initially dry soil profile. Hence, z_{sf} is equivalent to the maximum depth of soil-water penetration, z_{wf}, after the infiltration/redistribution event. This equation, (Eq. 2-18), is only valid for solutes applied on the soil surface. If a solute is assumed to be arbitrarily located at a depth z_i before the infiltration event, then if I cm of water have infiltrated, the solute front position will be located at

$$z_{sf} = z_i + I/\theta_{fc} \qquad (2\text{-}20a)$$

However, the initial soil-water content in the soil profile has been reported to greatly influence the position of soil-water wetting front (Ghuman et al., 1975, Ghuman and Prihar, 1980, and Kirda et al., 1973). By combining the expression for the depth of water wetting front at an initial soil moisture θ_i ($z_{wf} = I/(\theta_{fc} - \theta_i)$; $\theta_{fc} > \theta_i$) and the expression for the depth of solute front location ($z_{sf} = I/\theta_{fc}$) we get

$$z_{sf}/z_{wf} = (1 - (\theta_i/\theta_{fc})) \quad , \theta_{fc} > \theta_i \qquad (2\text{-}20b)$$

Equation (2-20b) illustrates the fact that a non-adsorbed solute will lag behind the wetting front as long as $\theta_i > 0$. If $\theta_i = 0$, i.e., for an initially dry soil, $z_{sf} = z_{wf}$. If $\theta_{fc} = 0$, then $z_{wf} = I/(\theta_{fc}-\theta_i)$ is undefined, but from (2-20b) $z_{sf}/z_{wf} = 0$, so that under these circumstances (2-20b) is not valid.

For adsorbed solutes, like NH_4^+-N, equation (2-20) must be modified to account for the adsorption-desorption process. The rate of solute transport is reduced by a factor R $(1+(\rho/\theta)\ K_D)$ (equation (2-5b)). Thus, the solute peak can be calculated from

$$z_{sf} = z_i + (I/\theta_{fc})(1/R) \qquad (2\text{-}21)$$

where R is called the retardation factor and is an index of retardation of NH_4^+-N leaching in soils owing to the adsorption/desorption process.

Although the evapotranspiration demand does not alter the solute peak location, it creates a deficit, I_d, above the solute peak, that must be overcome by an infiltration event, I, before the solute moves from say depth z_i to z_{i+1}. Let us assume that plant roots are extracting water from a static soil profile (i.e., $\partial\theta/\partial t = 0$ in equation (2-11)) then the deficit, I_d, that has to be overcome by I before the solute peak moves can be calculated from equation (2-22).

$$I_d = \int_0^{z_{sf}} (\theta_{fc} - \theta(z))\ dz \qquad (2\text{-}22)$$

where $\theta(z)$ = soil-water content, $cm^3\ cm^{-3}$, calculated from equation (2-11), with $\partial q/\partial z = 0$.

z_{sf} = depth of solute peak, cm, calculated from (2-21), and

I_d = deficit created by water extraction

The effective amount of water, I, that can displace the solute front is $I_e = I - I_e$. If $I_e > 0$, the new solute front is located at

$$z_{sf} = z_i + (I_e/\theta_{fc})(1/R)\ ; \qquad I_e > 0 \qquad (2\text{-}23)$$

If $I_e < 0$, then the event does not overcome the deficit. The solute peak location is then unchanged, i.e.,

$$z_{sf} = z_i \qquad (2\text{-}24)$$

After the soil-water deficit created by evapotranspiration is satisfied, the remaining soil-water is distributed to a new depth z_x by successive approximations to satisfy the condition

$$I - 2ET = \int_0^{z_x} (\theta_{fc} - \theta(z))dz, \quad z_x > z_{sf} \tag{2-25}$$

where z_x is the depth to which water was infiltrated. The factor of 2 on ET, reflects the assumption that the redistribution period takes 2 days.

Since equation (2-18) was derived by neglecting the effects of diffusion and dispersion, the prediction of solute fronts should be considered an approximation. Rose et al. (1981) have demonstrated that for conservative solutes applied on soils with homogeneous soil profiles that drain to a uniform field capacity (θ_{fc}) soil-water content, the solute peak location is overpredicted by approximately 10%.

The PDM presented here is only capable of estimating solute peak locations in well-drained homogeneous soil profiles assumed to be at a constant soil-water content. It is not capable of simulating transient soil-water and solute dynamics in heterogeneous or layered soils. In order to improve on some of these limitations, Rao et al. (1981) developed an improved "hybrid" management oriented nitrogen model, NITROSIM which can be viewed as the "extended" PDM. NITROSIM is capable of simulating the fate (transport, retention, transformation and uptake) of applied inorganic nitrogeneous species in heterogeneous soil profiles. A detailed mathematical analysis of NITROSIM is presented elsewhere (Rao et al., 1981).

Summary

This literature search has been concerned with the characterization of nitrogen behavior in the soil-plant-atmosphere continuum for increased corn production and reduced groundwater pollution. The inadequacy of the crop response curves in defining N and water deficits has been examined. The new concepts advocated by Greenwood et al. (1965) have been presented. Both concepts will continue to be used until researchers are able to identify all input crop production variables that interact simultaneously to determine final crop yield.

Improved systems of management for soil, water and nitrogen have been reviewed to show their potential use under Florida conditions. Because such systems require complete characterization of N (retention, transport, transformation and plant uptake), the bulk of the review chapter has been concerned with current concepts in modeling nitrogen dynamics in soils.

Research oriented models, developed from the more comprehensive miscible displacement theory, have been presented. The failure to obtain exact analytical solutions from these models (except under saturated flow conditions) led to the intensive implementation of numerical methods that utilize computational facilities. However, the exact specification of the physical and chemical parameters have been fraught with the problems of soil spatial variability (and to some extent, the instability characteristics of the numerical schemes used). This facilitated the development of simplifed mathematical models which utilize the earlier chromatographic concepts and have been found to be appropriate for field use application. These management oriented models are simple, inexpensive, and simulate the real physical system with a reasonable degree of accuracy.

CHAPTER 3

METHODS AND MATERIALS

Gainesville Corn Experiment

The corn field experiment at Gainesville, Florida, was carried out under irrigated and rainfed conditions. The resulting data were utilized in verifying the nitrogen model -- NITROSIM (Rao et al., 1981). The model input parameters were derived from earlier studies (Rao et al., 1981; Mutti, 1984).

The experiment was conducted at the Irrigation Research and Education Park (Unit 2) at Gainesville, Florida. This experiment was part of a larger interdisciplinary research project aimed at studying the effects of applied water and nitrogen on corn growth and the final grain yields. This cooperative effort involved faculty from the Departments of Soil Science (Drs. L. C. Hammond and P. S. C. Rao), Agronomy (Dr. J. M. Bennett) and Agricultural Engineering (Dr. J. W. Jones).

The soils are classified as a Millhopper fine sand, a member of the loamy, hyperthermic family of Grossarenic Paleudults (Calhoun et al., 1974). Detailed soil physical and chemical data for this soil series are given elsewhere (Calhoun et al., 1974).

The experiment was laid out as a split plot design (Fig. 3-1). Three water treatments (rainfed, W_0; reproductive water stress, W_1; and optimum irrigation, W_2) were superimposed on two cultivation treatments (conventional cultivation, C_0; and subsoiling, C_1) resulting in six water-cultivation treatments (1, 2, 3-S, 4-S, 5, 6-S; Table 3-1) as the main plots. Irrigation water was applied in the optimum irrigation

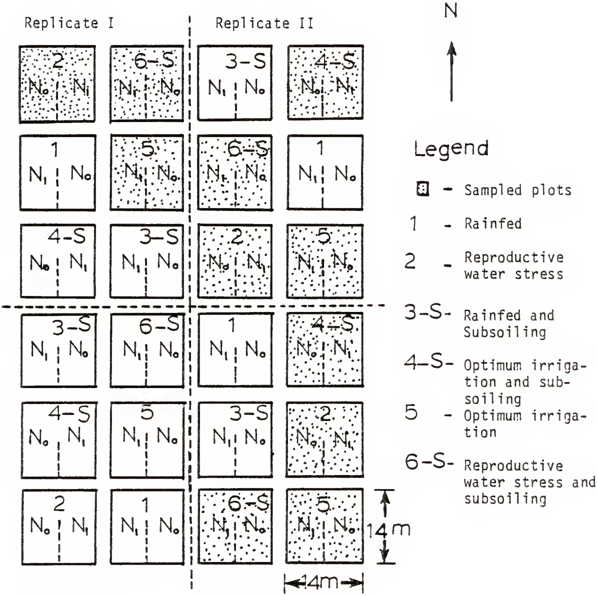


Fig. 3-1 Field Plot Layout at Irrigation Research and Education Park (IREP), Unit 2, Gainesville, Florida, 1983

Table 3-1 Water-cultivation and fertilizer N treatments, Irrigation Research and Education Park, Gainesville, Florida, 1983

Treatment number	Code	Treatment Description
	Main Plots	
1	W_0C_0	Rainfed without subsoiling.
2	W_1C_0	Reproductive Water Stress Irrigated when soil-water pressure head at 15 cm soil depth reached 200 cm of H_2O except for a two-week imposed soil-water stress initiated at tasseling (85 days after planting).
3-S	W_0C_1	Rainfed + Subsoiling.
4-S	W_2C_1	Optimum irrigation + subsoiling. Irrigated when soil-water pressure head at 15 cm soil depth reached 200 cm of H_2O.
5	W_2C_0	Optimum water without subsoiling Same as in 4-S above.
6-S	W_1C_1	Reproductive Water Stress + Subsoiling. Same as in 2 above.
	Sub-Plots	
-	N_0	Low nitrogen (168 kg N ha^{-1}) Vegetative N stress. Banded sidedress applications of 38, 29, 57 and 43 kg N ha^{-1} were applied 25, 49, 77 and 98 days after planting, respectively.
-	N_1	Optimum nitrogen (413 kg N ha^{-1}) Sufficient nitrogen conditions during all the growth stages. Banded sidedress applications of 38, 81, 111, 67 and 116 kg N ha^{-1} were applied 25, 49, 56, 63 and 84 days after planting, respectively.

Table 3-2 Rainfall and irrigation amounts at Irrigation Research and Education Park, Gainesville, Florida, 1983

Date	T*	Water Input		
		R#	Irrigation	
		W_0	W_1	W_2
		cm		
2/25	1	0.76**		
2/28	4	0.51		
3/01	5	0.41		
3/07	11	7.09		
3/10	14	0.23		
3/15	19	0.69		
3/16	20	0.89		
3/17	21	2.79		
3/18	22	1.22		
3/21	25	1.78		
3/24	28	1.30		
3/27	31	0.76		
3/28	32	0.03		
3/31	35	0.76		
4/04	39		1.52	1.52
4/07	42	1.22		
4/08	43	1.37		
4/09	44	2.64		
4/10	45	0.10		
4/15	50	3.33		
4/18	53	0.05		
4/19	54	2.24		
4/24	59	7.49		
5/03	68		1.27	1.27
5/04	69	2.54		
5/10	75		2.29	2.29
5/12	77	0.10		
5/16	81		1.27	1.27
5/17	82	7.14		
5/23	88			1.78
5/27	92			2.54
5/29	94	0.66		
5/30	95	0.23		
6/01	97	2.03		
6/03	99			
6/04	100	1.07		
6/05	101	1.52		
6/06	102	1.63		
6/07	103	1.91		
6/08	104	5.53		
6/12	108	0.13		
6/13	109	0.66		
6/15	111		1.27	1.27
6/17	113		1.52	1.52
6/20	116		1.27	1.27
6/21	117	0.15		
6/22	118	0.18		
6/23	119	0.13		
6/24	120	1.98	1.91	1.91
6/25	121	0.23		
6/26	122	8.08		
6/29	125	1.09		
6/30	126	1.42		
7/01	127	0.08		
7/03	129	0.13		
7/04	130	1.55		
7/05	131	0.10		
7/06	132	1.17		
7/08	134	1.04		
7/12	139	1.68		
7/14	140	0.28		
Totals		80.1	14.9	18.7

W_0 - Rainfed, W_1 - reproductive water stress, W_2, optimum irrigation.

T* - Day after planting.

** - 0.76 cm is irrigation water that was applied to all treatments and counted as rainfall.

R# - Rainfall

treatment (W_2) when the profile soil-water pressure head at 15 cm soil depth approached 200 cm H_2O as measured by mercury manometer tensiometers. The reproductive water stress treatment was the same as W_2, except for an imposed two-week stress period during the reproductive growth stage. The rainfed treatment received rainfall only, except for an irrigation of 0.76 cm that was applied on the day of corn planting. These six treatments were split for two levels of nitrogen (N_0 and N_1) which formed the subplots. The low level of nitrogen (N_0) was designed to induce vegetative nitrogen stress conditions, while the high level of nitrogen (N_1) was designed to provide sufficient nitrogen conditions throughout the growing season. This resulted in twelve treatment combinations that were replicated four times in a randomized block design (Fig. 3-1).

Treatments 3-S, 4-S, and 6-S were superimposed on subsoiled plots (C_1), while treatments 1, 2, and 5 were applied on conventionally tilled plots (C_0). Thus, treatments 3-S, 4-S and 6-S were, respectively, equivalent to 1, 2 and 5 in terms of water input, but differed in terms of cultivation treatments only. The subsoiling treatment was designed to break the plow layer which occurs between 30 and 45 cm soil depth. Six chisels that were spaced 30 cm apart were used to achieve this operation. The water input distribution during the growing season is presented on Table 3-2. Fertilizer nitrogen, in the form of NH_4NO_3, was surface banded on the east side of each row. The fertilizer band was approximately 6 cm wide and about 30 cm from the row. These water-cultivation and N treatments are presented on Table 3-1.

For this study, soil and plant samples for nitrogen and soil-water content analysis were collected in the following treatments: $W_1C_0N_0$

($2N_0$), $W_1C_0N_1$ ($2N_1$), $W_1C_1N_0$ ($6\text{-}SN_0$), $W_1C_1N_1$ ($6\text{-}SN_1$), $W_2C_0N_0$ ($5N_0$), $W_2C_0N_1$ ($5N_1$), $W_2C_1N_0$ ($4\text{-}SN_0$) and $W_2C_1N_1$ ($4\text{-}SN_1$), Fig 3-1. Two soil sampling sites were randomly selected from each plot. Soil samples were collected by hand auger in 15 cm soil depth increments up to 105 cm. Soil samples from corresponding depth increments were mixed and stored in plastic bags. Two plant samples (above ground plant parts only) were also randomly selected from each plot close to soil sampling sites. These were separated into stems, leaves, reproductive parts (silk+cob+tassel+husks) and grain depending on the stage of corn growth and the time of sampling. These plant and soil samples were collected in eight treatments only because the resultant data were sufficient to meet the present objectives. Also, shortage of labor prevented extensive soil and plant sampling. Nitrogen application dates are shown on Table 3-3.

Field Operations

Before planting (in late January and early February) half the plots were subsoiled to a depth of between 30 and 45 cm using chisels that were spaced 30 cm apart. The remaining plots were conventionally disked and roto-tilled. In mid-February, fertilizer mixture 0-6-25 (together with micronutrients: 6.5% Mg, 0.75% Zn, and 0.25% B) was broadcast at a rate of 130 kg ha^{-1} (116 lbs A^{-1}). During the same period Soil Brom 85 was applied at the rate of 44 L ha^{-1} (4.7 gal A^{-1}). On February 23rd, Furdan 10 G, Sutan and Atrazine were applied at the rates of 22 kg ha^{-1} (19.4 lbs A^{-1}), 4.4 L ha^{-1} (3.75 pints A^{-1}) and 2.3 L ha^{-1} (1 quart A^{-1}), respectively. After these applications, the experimental plots were disked.

Table 3-3 Nitrogen application, soil and plant sampling dates, IREP, Gainesville, Florida, 1983

Date	Days after planting	Soil sampling	Plant sampling	N Applications	
				N_0	N_1
				---- kg ha^{-1} ----	
Feb 21	-3	+	-	-	-
March 7	11	+	-	-	-
March 21	25	+	-	+	+
March 29	33	+	-	-	-
April 13	48	+	-	+	+
April 21	56	-	-	-	+
April 27	62	+	-	-	-
April 28	63	-	-	-	+
May 2	67	-	+	-	-
May 11	76	-	+	-	-
May 12	77	-	-	+	-
May 19	84	-	-	-	+
May 23	88	-	+	-	-
May 27	92	+	-	-	-
June 2	98	-	-	+	-
June 11	107	+	+	-	-
June 25	121	+	+	-	-
July 18	144	+	+	-	-

+ Means the corresponding field operation was carried out.

- Means the corresponding field operation was not carried out.

On February 24 and 25, 1983, 2 corn seeds (Zea Mays L., var. "McCurdy 84aa") were hand planted (2 seeds per planting station) in plots (14x14 m) consisting of 21 rows spaced 61 cm apart. Within row spacing was 23 cm. Corn plants were later thinned to 1 plant per planting station on May 5. This gave a plant population that was approximately 72,000 plants per hectare. Because of severe winds, a cold spell and nematode infestation, corn establishment was poor in all plots except replicate IV. After Nemacur 15G application and favorable weather conditions, the other replicates improved considerably, but did not surpass replicate IV. Corn was harvested on July 18, 1983 (144 days after planting).

The rainfall and irrigation treatments during the growing season (February 24 - July 18, 1983) are given on Table 3-2. The times of soil and plant sampling are indicated on Table 3-3.

The various crop husbandry practices (e. g., weeding, insect and pest control, etc.) and the measurement of other soil and crop parameters including leaf water potential, soil water potential, carbon dioxide exchange rate, dry matter accumulation, were recorded and will be reported elsewhere by other members of the multidisplinary research team.

Laboratory Methods

Soil physical and chemical analysis data. A subsample was taken from each soil sample for gravimetric soil-water content determination. The gravimetric soil-water contents were converted to volumetric soil-water contents by multiplying the gravimetric soil-water content with the corresponding soil bulk density value for that depth increment. The soil bulk density values used were: 1.53 (0-15 cm), 1.54

(15-30 cm), 1.60 (30-45 cm), 1.58 (45-60 cm), 1.55 (60-75 cm), 1.55 (75-90 cm) and 1.54 g cm^{-3} (90-105 cm). The rest of the sample was oven dried at between 50 and 70 C and stored in plastic bags for later determination of nitrogen (NH_4^+-N and NO_3^--N).

The total amounts of water in the 15 cm soil depth increments or the whole soil profile (L = 105 cm) were calculated by multiplying the volumetric soil-water content value with the soil depth increment or by multiplying the average soil profile water content value with the soil profile length (L).

The amount of deep percolation (i.e., water leaving the 105 cm soil depth) for any given period between soil samplings during the growing season was estimated from the following water balance expression

$$DP_j = W_{j,i} + W_j - ET_j - W_{j,f} \tag{3-1}$$

where DP_j = deep percolation for time period j.

$W_{j,i}$ = measured initial profile water in the 105 cm soil depth at the beginning of period j

W_j = measured water input (W_j = rainfall + irrigation) for period j

ET_j = actual evapotranspiration for period j, and

$W_{j,f}$ = measured final profile water in the 105 cm depth at the end of period j.

The actual evapotranspiration data were obtained from NITROSIM, which utilizes potential evapotranspiration data calculated by the Penman equation. Nitrate and ammonium nitrogen were determined by the Kjeldahl stem distillation procedure (Bremner, 1965b). The total amounts or integral amounts of nitrogen residing within the soil profile at a given time were calculated as follows:

$$M_t = \sum_{i=1}^{n} (C_i)(\rho_i)(\Delta z_i); \quad i = 1, n \qquad (3\text{-}2)$$

where M_t = total amount of N (NH_4^+-N or NO_3^--N), μgN cm^{-2}.

= soil bulk density of the ith depth increment, g cm^{-3}; i=1,n

C_i = nitrogen (NH_4^+-N or NO_3^- N) concentration in the ith depth increment, μgN g^{-1} soil; i=1,n

Plant analysis data. Plant samples were dried at between 50 C and 70 C in the oven. The dried samples were weighed and ground to pass through a 1 mm sieve. Subsamples were collected from each finely ground nitrogen.

A 200 mg plant sample was placed in a graduated pyrex Folin-Wu digestion tube to which 4.4 ml of digestion mixture (420 ml conc. H_2SO_4 + 350 ml of 30% H_2O_2 + 14 g $LiSO_4$ + 0.42 g Se) was added. The digestion tubes were placed in an aluminium digestion block that was preheated to 200 C. The temperature was then raised to 340 C. Heating continued until the solution cleared. The samples were then cooled at room temperature and diluted to 50 ml with deionized water. A 10 ml aliquot was withdrawn from each sample and stored in a plastic vial for potassium determination (the results of which will be reported elsewhere). The remaining 40 ml was steam distilled (Kjeldahl procedure, Bremner, 1965a) using a strong base (10 N NaOH). The distillate was collected in 2% boric acid indicator and titrated with a strong acid (0.1 N H_2SO_4).

Nitrogen uptake data were obtained by multiplying nitrogen concentrations with the corresponding dry matter yield and the average plant population to give N uptake per unit area (kg N ha^{-1}).

Nitrogen Use Efficiency (NUE) was calculated from expression (3-3).

$$\text{NUE} = \frac{\text{cumulative plant N uptake}}{\text{Total fertilizer input}} \qquad (3\text{-}3)$$

Statistical analyses were performed using the methods described by Steel and Torrie (1960).

Malawi Studies

Field studies were conducted in Malawi to measure soil physical and chemical characteristics that are important in characterizing nitrogen dynamics in the soil. Bulk soil samples and undisturbed soil cores were collected at some locations in Malawi. Soil physical and chemical data for the Lilongwe series were used as input parameters in the NITROSIM model. Field data to verify these model simulations, however, were not collected. The simulation studies were intended to provide guidelines in the design and evaluation of future field experiments on nitrogen practices that increase nitrogen use efficiency and reduce groundwater pollution.

Field Experiment

A field experiment was conducted at Chitedze Research Station (114^o S, 34^o S; 1150 m (3770 ft) above sea level) in 1982 to determine *in situ* hydraulic properties of the Lilongwe series. The instantaneous profile method (Watson, 1966; Davidson et al., 1969) was used to measure total soil-water pressure heads as a function of depth and time. Two square plots (2.2 x 2.2 m) were demarcated adjacent to each other in Block D. Four tensiometers were installed at each of the six depths (15, 30, 45, 60, 75 and 90 cm) in the two plots following the procedures outlined by Davidson et al. (1969). When the whole soil profile (0-90 cm) was saturated, total pressure heads were recorded every three hours for the first two days and three times a day thereafter (starting from September 1 to October 20, 1982). Soil-water charactistic curves were measured using undisturbed soil cores collected adjacent to the two plots. These curves were used to convert measured soil-water pressure heads (h) to volumetric soil-water contents (θ). The values of total soil-water head (H) and volumetric soil-water contents were then used to calculate hydraulic conductivity values at different depths.

Brown and Young (1965) have classified the Lilongwe series as a Ferruginous Latosol (using the Inter-African Pedological Service Classification system). M. Lowole of the Soil Survey Department, Lilongwe, Malawi, (personal communication) has classified this soil as a Ferric Luvisol (Food and Agricultural Organization classification system) or as a Ferric Rhodustalf (U. S. Soil Taxonomy). A soil profile description on the experimental site has recently been given by M. Lowole (personal communication, Appendix 1. Table A1-1).

Soils of the Lilongwe series are characterized by a strongly developed fine or medium blocky structure in the subsoil (Appendix 1; Tables A1-1 and A1-2) with well-defined clay coated peds or aggregates. Lilongwe soils are well-drained with an average bulk density of 1.3 g cm^{-3} (Saka, 1979, unpublished data). The soil reaction is classified as moderate (pH (H_2O) = 5.0 to 5.5) with a base saturation of between 50 and 80% in the subsoil. The soil surface (0-15cm) cation exchange capacity is approximately 20 meq $(100g\ soil)^{-1}$.

The rainfall and temperature regimes have been classifed as moderate (Anonymous, 1962). Rainfall averages 89 cm (35") per year with most of it (ca. 85%) falling in the four wettest monsoon months between November and April (Appendix 4, Table A4-1). The mean annual temperature varies between 20 and 21 C, with a mean minimum of 15.6 C in July and mean maximum of 24.6 C in November.

Undisturbed Soil Cores

Soil cores (3 cm diameter and 6 cm long) were collected from Lunyangwa, Mbawa and Lisasadzi for the determination of soil-water characteristics curves, hydraulic conductivity and soil bulk density.

Soil-water characteristic curves, for tensions less than 300 cm of H_2O were determined by the procedure described by Klute (1965b). Field capacity and wilting point soil-water contents (1/3 bar and 15 bars, respectively) were determined by the pressure plate equipment (Peters, 1965). Saturated hydraulic conductivity values were determined by the constant head method as outlined by Klute (1965a). The Green-Corey method (Green and Corey, 1971) was used to calculate hydraulic conductivity as a function of soil-water content for soil surface (0-15 cm) layers. Soil bulk density was determined by the core method as outlined by Blake (1965).

Disturbed Soil Samples

Disturbed soil samples were collected from Lunyangwa, Mbawa, Bulala Extension Office, Ehehleni Turn Off, Lisasadzi, Mchinji, Chitedze, Salima, Mwanza, Kasinthula and Ngabu (Fig. 3-2). These were analyzed for particle size analysis, pH and zero points of charge.

The pipette method (Day, 1965) was employed in the determination of various soil separates (Table 3-4). The soil pH was determined both in water (1:1 soil to water ratio) and in 1N KCl (1:1 soil to 1N KCl solution ratio) using a glass electrode (Peech, 1965). The method of

Van Raij and Peech (1972), modified to exclude washing with dilute HCl and water, was employed in the determination of zero points of charge.

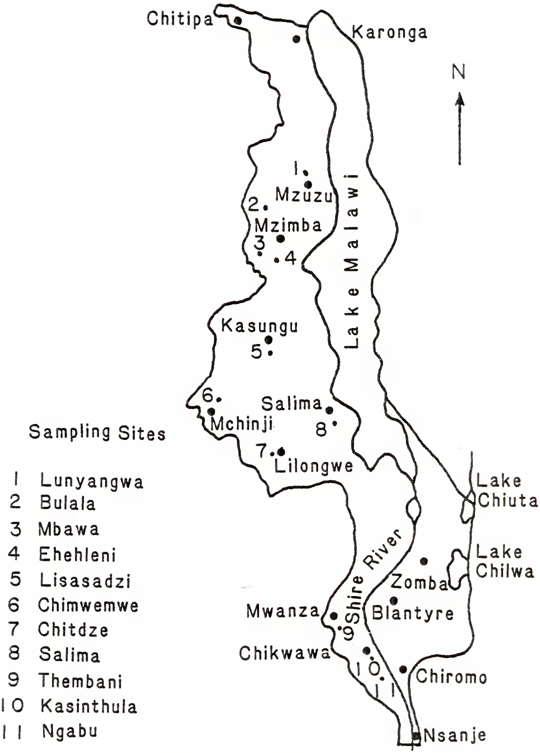


Fig. 3-2 Map of Malawi (Scale appro. 1:4,000,000)

Table 3-4 Particle size analysis for selected Malawi soils

Location	Depth	Sand	Silt	Clay	Classification*
	-cm-	----------	%	----------	
Ngabu (Field #6)	0-45	33	29	38	CL
Ngabu (Black Vertisol)	0-45	12	35	65	C
Ngabu (Brown Vertisol)	0-45	7	24	69	C
Mchinji-Chimwemwe	0-45	85	6	9	S
Salima ADD	0-30	24	26	50	C
Mwanza-Thembouni	0-30	81	15	4	LS
Kasinthula	0-30	66	19	15	SL
Lunyangwa (Uncultivated soil)	0-15	46	17	37	SCL
Lunyangwa (Uncultivated soil)	15-30	45	11	44	SC
Lunyangwa (Cultivated soil)	0-15	53	19	28	SCL
Lunyangwa (Cultivated soil)	15-30	54	14	32	SCL
Bulala	0-15	84	8	8	LS
Bulala	15-30	82	9	9	LS
Mbawa-1	0-15	82	13	5	LS
Mbawa-1	15-30	81	13	6	LS
Mbawa-2	0-15	53	24	23	SCL
Mbawa-2	15-30	55	21	24	SCL
Ehehleni Turn Off	0-15	71	17	12	SL
Lisasadzi	0-15	82	11	6	LS
Lisasadzi	15-30	85	10	5	LS

* C - clay, CL - clay loam, S - sand, LS - loamy sand, SL - sandy loam, SCL - sandy clay loam.

CHAPTER 4

WATER AND NITROGEN BEHAVIOR UNDER IRRIGATED CORN - GAINESVILLE FIELD EXPERIMENT

Soil-Water

The rainfall and irrigation distribution patterns for the 1983 growing season were presented on Table 3-2 (Chapter 3). The total amounts of rainfall and irrigation are summerized in Table 4-1.

Table 4-1. Rainfall and irrigation amounts during the growing season (February 24 to July 18, 1983) at IREP, Gainesville, Florida.

Treatment	Rainfall	Irrigation	Total
	---------------	cm	---------------
Rainfed (W_0)	80.1	-	80.1
Reproductive water stress (W_1)	80.1	14.9	95.0
Optimum irrigation (W_2)	80.1	18.7	98.8

There were five major rainfall events of 7.07, 7.49, 7.14, 5.53 and 8.08 cm, at 11, 59, 82, 104 and 122 days after planting, respectively. First signs of mid-day wilting of corn plants in the reproductive water stress treatment (W_1) plots were observed 85 days after planting. A reproductive water stress period was imposed for a period of 2 weeks, starting 85 days after planting. Prior to this, small showers of 0.66 and 0.32 cm of rain were recorded 94 and 95 days after planting, respectively.

Table 4-2 illustrates volumetric soil-water contents for two soil sampling dates in the various treatment combinations. Soil-water limiting situations in the upper soil furface layers are depicted for the reproductive water stress treatment (W_1) for May 25, 1983, while higher and nearly uniform profile soil-water contents are illustrated for June 11, 1984, in all treatment combinations.

Total amounts of soil-water stored within the soil profile (0-105 cm) in the 15 cm depth increments are presented on Table A2-1 (Appendix 2). Examination of these data reveal that there were small differences in stored profile soil-water between subsoiled and conventionally tilled plots. This, perhaps, demonstrates that the plow pan observed in these sandy soils (as reflected in increased bulk densities of up to 1.60 g cm^{-3} in the 30-45 cm depth range) does not create a severe barrier to water transport, although it is likely that it might provide mechanical impedance to root penetration. The data indicate that the resulting stored profile soil-water was influenced by the water management treatments and not by the cultivation treatments. Penetrometer readings recorded soon after planting (S. Jagtap; and J. W. Jones, personal communication) indicated that the subsoiling treatment was not effective enough in breaking the plow layer or that other cultivation treatments applied after the subsoiling treatment compacted the subsurface soil layers again. Small differences in profile soil-water stored between W_1 and W_2 (except during the reproductive stress period) are expected because the differential amount of water between these two is only 3.8 cm (Table 4-1).

Table 4-2 Volumetric soil-water content distribution in the soil profile for two soil sampling dates at IREP, Gainesville, Florida, 1983

Depth	$W_1C_0N_0$		$W_1C_0N_1$		$W_2C_1N_0$		$W_2C_1N_1$	
	May 25	June 11	May 25	June 11	May 25	June 11	May 25	June 11
-cm-				$cm^3\ cm^{-3}$				
0-15	0.012	0.059	0.012	0.059	0.056	0.058	0.043	0.055
15-30	0.031	0.065	0.021	0.068	0.054	0.068	0.039	0.074
30-45	0.053	0.078	0.029	0.076	0.049	0.074	0.044	0.079
45-60	0.059	0.086	0.066	0.082	0.055	0.081	0.051	0.079
60-75	0.058	0.076	0.042	0.082	0.063	0.085	0.056	0.074
75-90	0.060	0.073	0.043	0.088	0.050	0.077	0.057	0.073
90-105	0.058	0.078	0.046	0.079	0.043	0.077	.065	0.072
	$W_2C_0N_0$		$W_2C_0N_1$		$W_1C_1N_0$		$W_1C_1N_1$	
0-15	0.062	0.064	0.058	0.056	0.023	0.059	0.025	0.063
15-30	0.057	0.087	0.052	0.071	0.037	0.081	0.019	0.072
30-45	0.055	0.082	0.047	0.071	0.072	0.075	0.050	0.077
45-60	0.061	0.088	0.050	0.074	0.052	0.079	0.054	0.076
60-75	0.075	0.077	0.063	0.074	0.062	0.079	0.059	0.077
75-90	0.063	0.079	0.074	0.074	0.058	0.081	0.067	0.085
90-105	0.060	0.082	0.064	0.078	0.062	0.081	0.070	0.074

Nitrogen Behavior in the Soil Plant System

NH_4^+-N Concentration Profiles

Nitrogen content values (from soil analysis samples) were measured as a function of depth (7 depths) and time (11 soil sampling times). In the present analysis, data for the last four sampling dates (May 25, June 11, June 25 and July 18) will be presented to illustrate nitrogen content variability in field soils.

Ammonium concentration profiles are depicted on Figs. 4-1 and 4-2. These are shown for either 2 or 3 replicates in the optimum irrigation (W_2) and reproductive water stress (W_1) treatments under high fertility conditions (N_1). The data in both treatments during the period under study exhibit a great deal of variability, especially in the surface soil layers. For example, on May 25, 1983, profile (0-15 cm) NH_4^+-N concentration values were 143 μg g^{-1} soil (range 77-232 μg g^{-1} soil) in the reproductive water stress treatment, $W_1C_0N_1$, and 119 μg g^{-1} soil (range 92-147 μg g^{-1} soil) in the optimum irrigation treatment, $W_2C_0N_1$. This trend is repeated for the other soil depths and times as well. The variability between replicates is minimal at deeper depths, but this is perhaps because little NH_4^+-N was detected at these depths.

For all sampling dates, maximum NH_4^+-N concentration occurs in the 0-15 cm depth and decreases in an exponential manner with depth. Very little NH_4^+-N (< 5 μg g^{-1} soil) is detected beyond 50 cm soil depth. Such behavior can be attributed to NH_4^+-N adsorption in the top soil layers and rapid transformation of NH_4^+-N to NO_3^--N. The occurrence of at least 10 μg g^{-1} soil in the top soil (0-15 cm) 60 days after

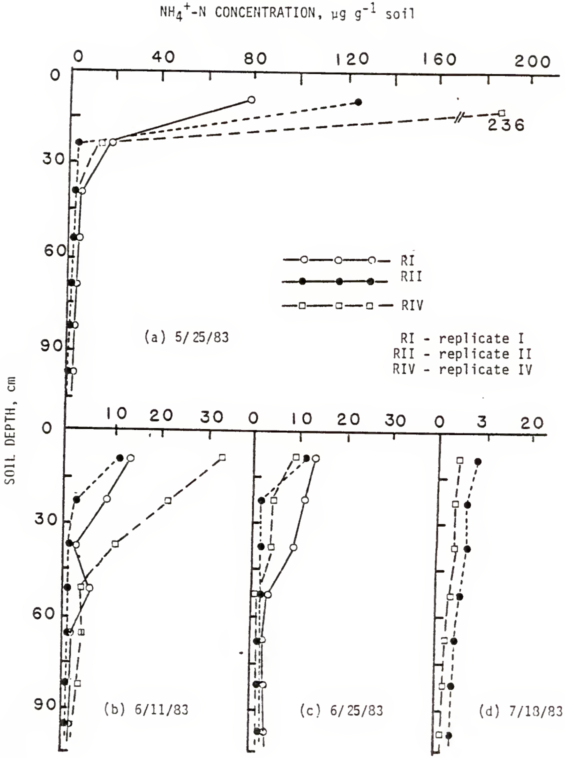


Fig. 4-1 Replicate NH_4^+-N Profile Concentration During Part of the Growing Season, at IREP, Gainesville, Florida, 1983, $W_1C_0N_1$

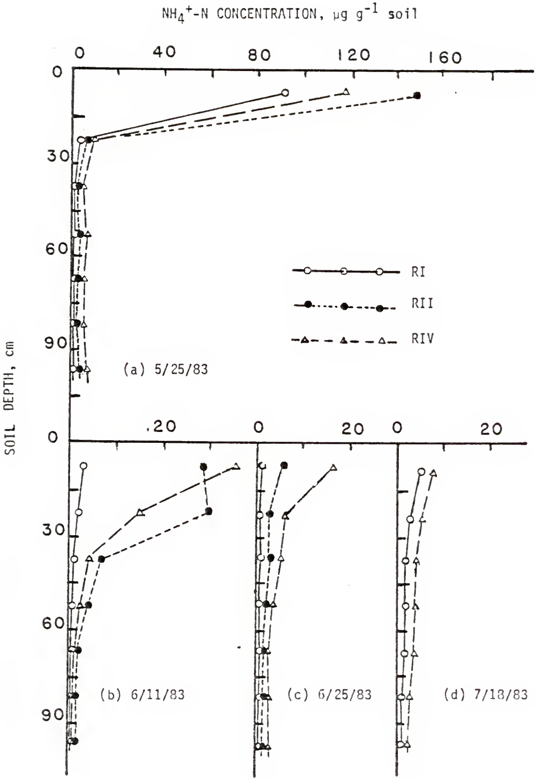


Fig. 4-2 Replicate NH$_4^+$-N Profile Concentration During Part of the Growing Season, at IREP, Gainesville, Florida, 1983, $W_2C_0N_1$

application (after a total of 44.15 cm of water) illustrates the importance of organic matter and clay content (even when they are present in small amounts) in retarding the mobility of adsorbed ions like NH_4^+-N. Similar observations were reported by Graetz et al. (1973) who detected very little amounts of NH_4^+-N at deeper depths (more than 30 cm) but at least 4 μg g^{-1} soil in the top 0-30 cm depth.

NO_3^--N Concentration Profiles

Figures 4-3 and 4-4 illustrate the movement of NO_3^--N under similar conditions to the ones presented earlier for NH_4^+-N. Large variability in NO_3^--N concentrations among the replicates, similar to that for NH_4^+-N, was observed. The NO_3^--N concentration profiles clearly demonstrate the importance of water as the major transporting agent of solution NO_3^--N in the soil profile. The solute peak concentration decreases with depth, except for Fig. 4-4c which exhibits two peaks. This double peak might be due to an earlier N application or NH_4^+-N nitrification in soil surface layers. The NO_3^--N concentration profiles become broader as the nitrate pulse is leached to greater depths. At harvest, less than 10 μg NO_3^--N g^{-1} soil was detected at all depths in the soil profile. These results illustrate the high mobility of the NO_3^--N ion in coarse-textured, permeable sandy soils. Westelaar (1962), Graetz et al. (1973), among many others, have observed similar behavior under field conditions.

NH_4^+-N and NO_3^--N Concentration Profiles

The differential leaching patterns for NH_4^+-N and NO_3^--N are illustrated in Fig. 4-5. Data for $W_1C_0N_1$ have been plotted on the same

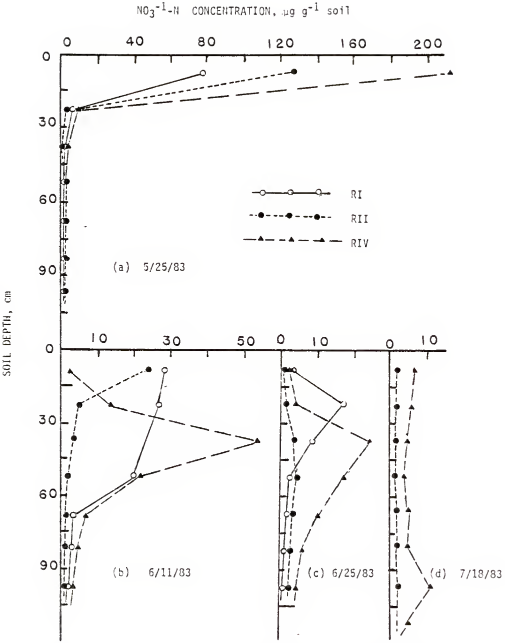


Fig. 4-3 Replicate NO_3^--N Profile Concentration During Part of the Growing Season, at IREP, Gainesville, Florida, 1983, $W_1C_0N_1$

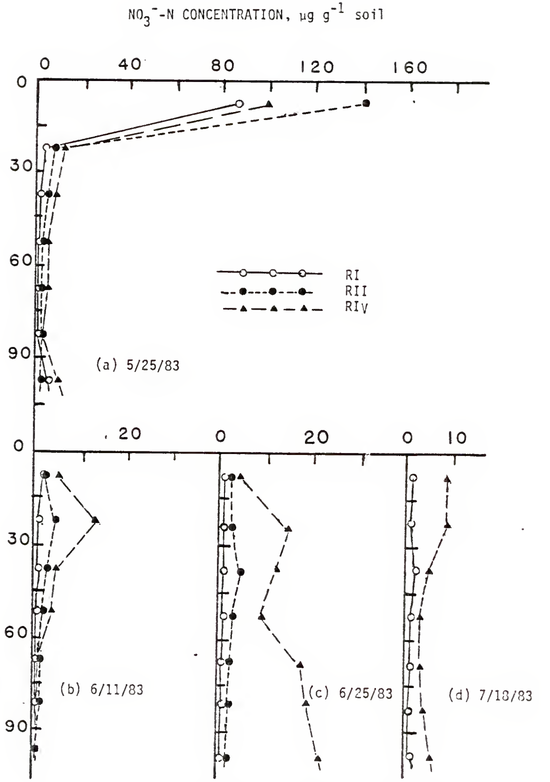


Fig. 4-4 Replicate NO_3^--N Profile Concentration During Part of the Growing Season, at IREP, Gainesville, Florida, 1983, $W_2C_0N_1$

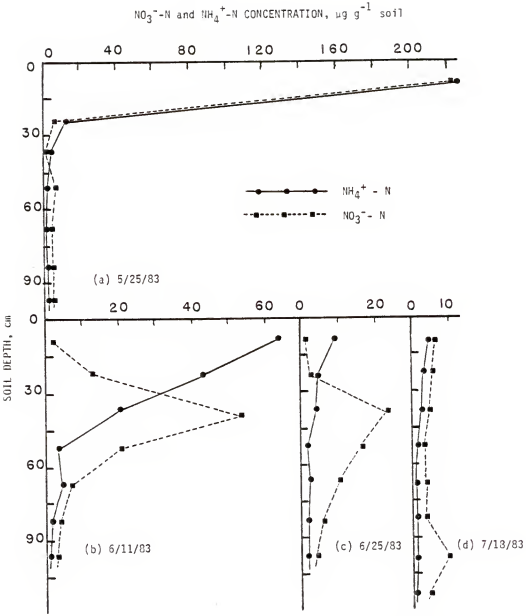


Fig. 4-5 NO_3^--N and NH_4^+-N Profile Concentration During Part of the Growing Season in Replicate IV, at IREP, Gainesville, Florida, 1983, $W_1C_0N_1$

graph for better comparison. Initially there were equal amounts of NH_4^+-N and NO_3^--N in the top soil layer (0-15 cm) (Fig. 4-5a). By June 11, 1983, both had been tremendously reduced. This can be attributed to various sinks of N, the most important of which are plant nitrogen uptake and leaching beyond the root zone. The loss of NH_4^+-N (through uptake and nitrification) is perhaps reflected in its reduced content and the broadening of the NO_3^--N peak. The broadening of the solute peak can be attributed to diffusive-dispersive flow and the addition of newly nitrified NO_3^--N from the NH_4^+-N pool in the soil surface layers. By the last day of sampling the soil profile had small quantities of NH_4^+-N and NO_3^--N, albeit a small peak of NO_3^--N at the bottom of the root zone (105 cm).

These results have illustrated many important and interesting points that are of practical consequences and significance for nitrogen field studies. Several factors that contribute to N content variability between treatments and replicates can be identified. The first is non-uniform fertilizer application. For example even when soil samples were collected on the day of N application (March 21, 1983) there was a large variation in soil surface concentration values. In the 0-15 cm depth increment, NO_3^--N concentrations varied from 86 to 844 $\mu g\ g^{-1}$ soil, with a mean value of 290 $\mu g\ g^{-1}$ soil and a coefficient of variation equal to 74%. The coefficients of variation were 52% and 49% for the 45-60 cm and 90-105 cm soil depths, respectively. The corresponding data (in high N plots for NH_4^+-N sampled in the 0-15 cm depth range on May 25, 1983, five days after nitrogen application and an irrigation amount of 1.78 cm) are 132 $\mu g\ g^{-1}$ soil (range 77 to 232 $\mu g\ g^{-1}$ soil) with 38% coefficient of variation.

Secondly, it has been observed that if soil samples were not collected on top of the fertilizer band, little (<1 μg g^{-1} soil) or no N was detected in the samples. Figure 4-2b illustrates that in one replicate there was less than 4 μg g^{-1} soil while in the other two replicates there was more than 28 μg g^{-1} soil in the 0-30 cm soil depth. Thus, non-uniform N application and the inability to sample on the site of N application seem to be the main physical barriers to nitrogen characterization under field conditions. Cameron et al. (1979) have reported that non-unform N application accounted for 38 to over 98% of the observed variation in the nitrogen content of their samples. The 38% CV for NH_4^+-N is within this range, so are the ones for NO_3^--N (73, 52 and 49%). Further, these results illustrate the fact that nitrogen moves vertically downwards in a narrow band with negligible lateral movement or spreading owing to the convective-dispersive process. Hornsby et al. (1984) also observed minimal lateral spreading of aldicarb nematicide when it was applied in small strips (bands) on Florida sandy soils planted to citrus. This finding also concurs with the observations made by Mutti (personal communication), who consistently sampled between corn plants, while N was applied between the rows, and detected no nitrogen in all his soil samples.

Thirdly, dissimilar leaching patterns have been observed for both NH_4^+-N and NO_3^--N under the present field conditions. Figures 4-2 to 4-5 all illustrate the differences in leaching patterns between replicates. Cameron et al. (1979) and Warrick et al. (1971) also observed variability in solute concentration profiles and attributed this to (i) nitrogen transformation, (ii) plant root uptake, (iii) variation in soil hydraulic parameters (intensity factors) caused by soil spatial variability and (iv) the microrelief created on the soil surface owing to non-uniform boundary conditions that are prevalent during water input periods. Saffigna et al. (1976) have observed non-uniform water infiltration patterns beneath the hills of sprinkler-irrigated potatoes. They attributed this behavior to stemflow and hilling. Soil spatial variability is illustrated by the work of Warrick et al. (1971), Balasubramanian et al. (1973) and Rao et al. (1973), among others, who have observed differential leaching patterns even when solutes were applied uniformly on the soil surface.

The points discussed above have important implications to agronomists, soil scientists and environmentalists. Firstly, for the soil scientist and environmentalist interested in solute transport in porous media, there is a danger of either overestimating or underestimating the potential hazard of solutes (or pollutants). If sampling is carried out on spots where the chemical was not applied nothing is recovered from such samples, although in some cases chemicals can be transported to sites other than their intended site of application. On the other hand, if sampling is done on the site where the chemical was applied, surprisingly large concentrations can be reported.

Secondly, for the agronomist who is interested in maximizing N uptake for maximum profit and grain yields, it appears that the method of N application is not important, although some methods are better and cheaper than others. The most important consideration seems to be the availability of the nutrient element within the plant roots domain of influence. Burns (1980) indicates that even if a small fraction ($<15\%$) of the root system is exposed to the nutrient element pool, it is able to compensate for the other parts of the root system, so that the crops demand can be met. Maybe this is why the most common agronomic practice is to concentrate nutrient application in a band, around the planting station, etc. However, what is overlooked is that, effectively, the plant is exposed to higher concentration of the nutrient element than is otherwise suggested by the nominal rate of application. As discussed earlier, this is one of the main sources of the observed nitrogen variability under field situations.

Because of this observed nitrogen variability in the soil profile, a second approach was taken to better characterize nitrogen behavior in the root zone. This involved calculating integral amounts of total N and/or individual N species, residing in the soil profile. The results for both NH_4^+-N and NO_3^--N illustrate the disappearance (through uptake, leaching beyond the root zone, etc.) of applied nitrogen as a function of time. These data are presented on Tables A2-2 and A2-3 (Appendix 2) for 15 cm depth increments. Table 4-3 illustrates soil profile nitrogen integral amounts for the last four sampling dates. Under low nitrogen fertility conditions the coefficients of variation ranged from 5 to 56%, while under high nitrogen fertility conditions the coefficients of variation ranged from 16 to 106%. These integral nitrogen masses are highly influenced by the variable soil profile nitrogen concentrations. Total masses calculated in two-dimensional space should provide a better characterization of nitrogen in a given soil volume compared to the one-dimensional analysis presented here. Nonetheless, these values are less variable when compared to profile concentration values.

Table 4-3 Soil profile (0-105 cm) integral amounts of nitrogen in different treatment combinations during part of the growing season at IREP, Gainesville, Florida, 1983

Date	RepI*	RepII	RepIV	Mean	CV	RepI	RepII	RepIV	Mean	CV
			$W_1C_0N_1$					$W_1C_0N_1$		
	------- kg ha^{-1} -------				-%-	-------- kg ha^{-1} --------				-%-
May 25	62	106	110	93	29	435	596	1136	722	51
June 11	41	34	66	47	36	327	156	548	344	57
June 25	32	51	58	47	28	168	72	196	145	45
July 18	-	-	79	-	-	-	89	115	102	18
			$W_1C_1N_0$				$W_1C_1N_0$			
May 25	75	148	159	128	35	1164	506	566	747	49
June 11	37	36	74	49	45	37	139	251	142	75
June 25	44	48	168	87	90	32	145	51	76	80
July 18	64	-	92	78	26	76	82	143	100	37
			$W_2C_1N_0$					$W_2C_1N_1$		
May 25	97	141	67	102	36	626	432	643	568	21
June 11	53	48	59	50	5	32	48	106	62	63
June 25	53	57	58	56	5	66	64	48	59	17
July 18	64	274	118	152	72	57	226	-	142	85
			$W_2C_0N_0$					$W_2C_0N_1$		
May 25	83	250	129	154	56	457	706	608	590	21
June 11	37	62	69	56	30	42	182	202	142	61
June 25	76	61	60	66	14	32	72	297	134	106
July 18	133	65	-	99	48	55	-	142	99	63

*Rep I - replicate I, RepII - replicate II, RepIV - replicate IV

CV - % coefficient of variation.

Figure 4-6, illustrates the total amounts of N for the same four sampling dates. The graphs indicate that there was a tendancy for N to increase at the end of the growing season. Three reasons can be attributed to this observation. The first is that after crop maturity N uptake is virtually stopped. The second reason is that the mineralization of organic matter can contribute to this increase, although these sandy soils have very little organic matter in the top soil layers. The third reason can be attributed to N variability. It is possible that the last samplings were more representative (in terms of sampling on or closer to the nitrogen band) compared to earlier samplings.

Three methods have been used to characterize N in field soils. This was an effort to resolve the problems associated with N variability under field conditions.

Effects of Water and Nitrogen on N Concentration and Uptake, Grain Yields and Dry Matter Accumulation

Total N Concentration in Corn Plant Parts

Nitrogen concentrations in plant vegetative parts (leaves and stems), reproductive parts (silk+tassel+cob+husks), and grain are depicted on Fig. 4-7. Nitrogen content values vary with the growth stage, time of the growing season, the plant part sampled, and in response to water and nitrogen fertility levels. There are small differences due to subsoiling, which can be attributed to sampling errors and not to the subsoiling treatment.

During the early part of the growing season, nitrogen content is high in the corn plant. This can be ascribed to the low demand for N by

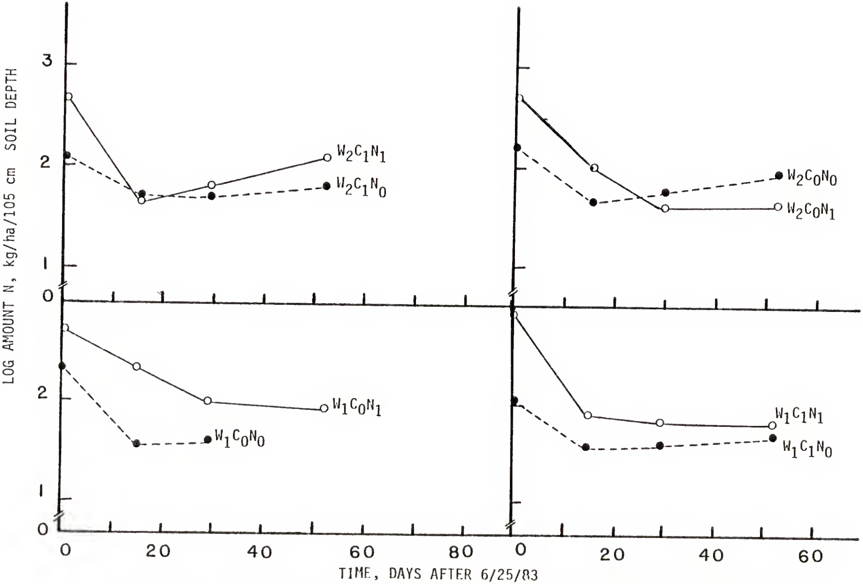


Fig. 4-6 Total N in the Soil Profile During Part of the Growing Season (May 25 to July 18, 1983) at IREP, Gainesville, Florida

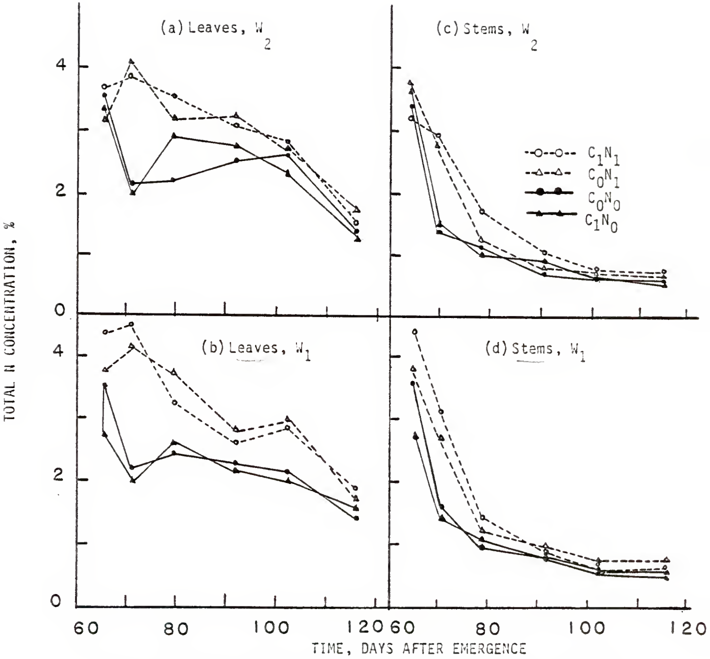


Fig. 4-7 Total N Concentration in Plant Components During the Growing Season

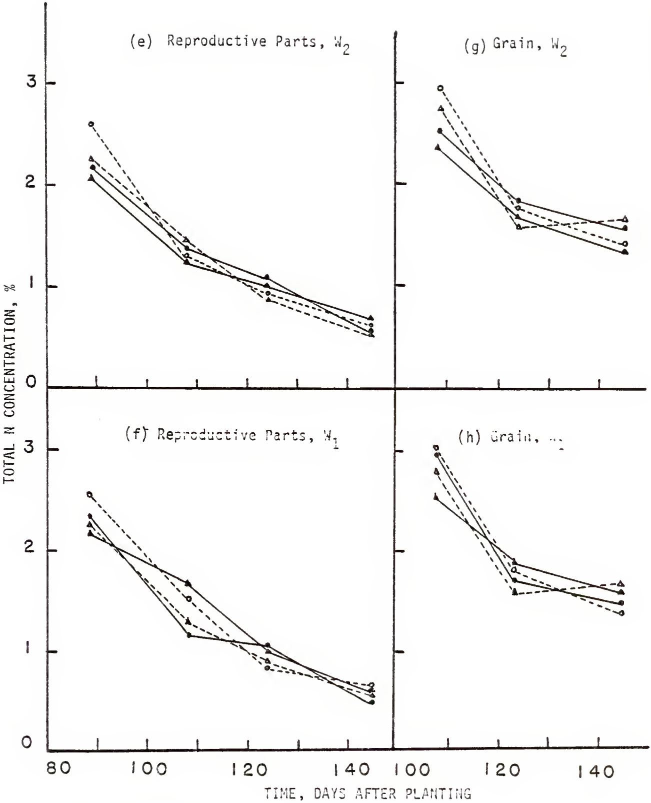


Fig. 4-7---Continued

the young plant. There is a sharp decline in N content as the plant enters the vegetative stage. This is when there is great demand for N by the plant as dry matter accumulation increases (Appendix 2, Table A2-4). This decline continues as more N is utilized in grain formation. By the end of the season low levels of N are detected in all plant parts.

Leaf nitrogen concentrations (Fig. 4-7a,b) show consistent fluctuations during the growing season. Higher nitrogen contents were found in high fertility plots (N_1) compared to low fertility plots (N_0) at all times during the season. This result is expected because N uptake is directly dependent on the amount of available N uptake when soil-water conditions are not limiting. Under both low and high N fertility levels there was a tendancy for N content to increase when soil-water conditions were limiting. This is also expected because when water is limiting, N uptake, translocation and assimilation are also reduced resulting in higher plant N contents and reduced dry matter production. However, large differnces in leaf N contents were observed between low and high N fertility plots during the second sampling period. It should be remembered that at this stage of growth both W_1 and W_2 had similar near stressing soil-water conditions. The only difference is that N_1 plots had sufficient nitrogen, while N_0 plots were under the vegetative nitrogen stressing conditions. The slight increase of N in N_1 plots is therefore due to available N in the root zone, albeit, near stressing soil water conditions, while the sharp drop in N contents in N_0 plots is indicative of both soil-water and nitrogen stressing conditions. However, it appears that before the onset of soil-water stress, the plant rapidly utilizes the available N, but as soil-water stressing conditions continue, the little N taken up by the plant tends to accumulate. These observations are consistent with the data reported by Nelson (1956), by Chandler (1960), and by Hanway (1962c). Mutti (1984) reported larger fluctuations in N content values during the growing season. This is because longer periods of soil-water stress were experienced in 1982 compared to 1983.

The nitrogen content in the stems exhibit similar decreasing trends as illustrated for leaf N. The only striking difference is that there is a definite sharp decline in N content as the plant enters the vegetative stages. There is also less variability in N content between treatments. Such observations indicate that stems quickly transport most of their N to other plant parts: the roots, the leaves and later the grain.

The reproductive parts indicate a gradual decrease in N content as the season progresses. This also illustrates N efflux to other plant parts, especially the grain. The data show very little variability between replicates and treatments.

The grain N content shows similar trends to those discussed above for the other plant parts. This is despite the fact that losses from the other plant components were assumed to have been translocated to the grain for storage and grain dry matter formation. The grain N content at the end of the season is essentially similar to that found in the leaves. These N values are within the common range (1.4-1.6%) reported in the literature (Kurtz and Smith, 1966). Mutti (1984) reported slightly higher N levels in the leaves compared to grain N at harvest. This difference is probably due to differences in environmental conditions between 1982 and 1983 or due to differnces in N uptake patterns in response to N fertility levels (as reflected in times of application), pests, diseases and rainfall distribution patterns.

Cumulative Nitrogen Uptake by Various Plant Parts

Nitrogen uptake by different plant components during the growing season are presented on Table A2-5 (Appendix 2). The data for conventionally tilled plots, under both N fertility levels (N_0 and N_1) and the two water management treatments (W_1 and W_2), are illustrated on Fig. 4-8. These data indicate that N uptake was highly influenced by both N fertility and water management treatments. There was more N uptake at the high level of N under sufficient soil-water conditions (W_2) compared to the low level of N under limiting soil-water conditions. Under limiting nitrogen conditions (N_0), N uptake was enhanced under sufficient soil-water conditions; while under sufficient nitrogen conditions (N_1), N uptake was reduced when soil-water was limiting, but picked up rapidly when soil-water was available. Thus N and water interactively influenced N uptake.

Figure 4-8 also illustrates the expected sigmoid-shaped curve for grain and total plant N uptake, while the uptake curves for other plant parts indicate an increase up to the silking stage and then a linear decrease up to the the end of the growing season. The rates of change of these curves give the influx of N to these plant components during the early part of the growing season up to silking, and the N efflux from these components during the later half of the season (from silking to maturity). Many investigators have reported this behavior of N accumulation and translocation in various plant parts. Among the important works in this area are the review article by Nelson (1956),

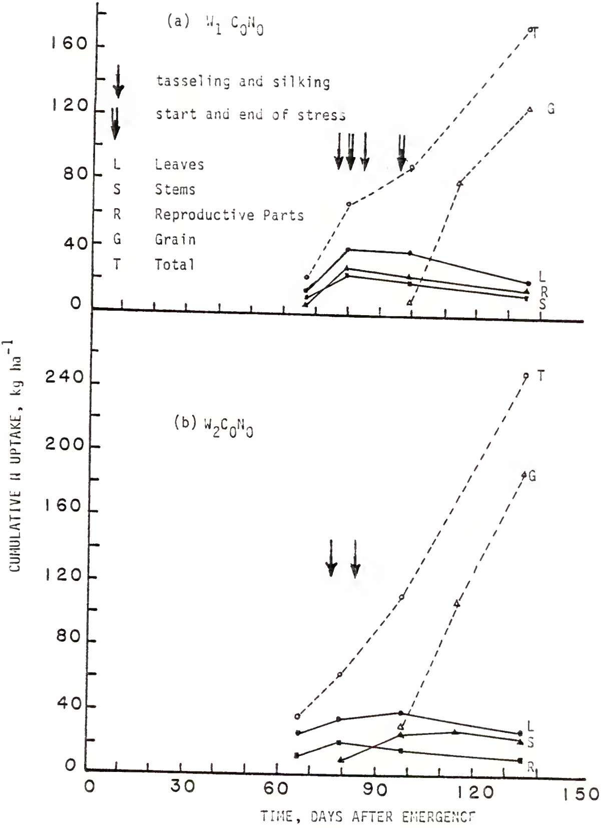


Fig. 4-8 Nitrogen Accumulation in Plant Components During the Growing Season

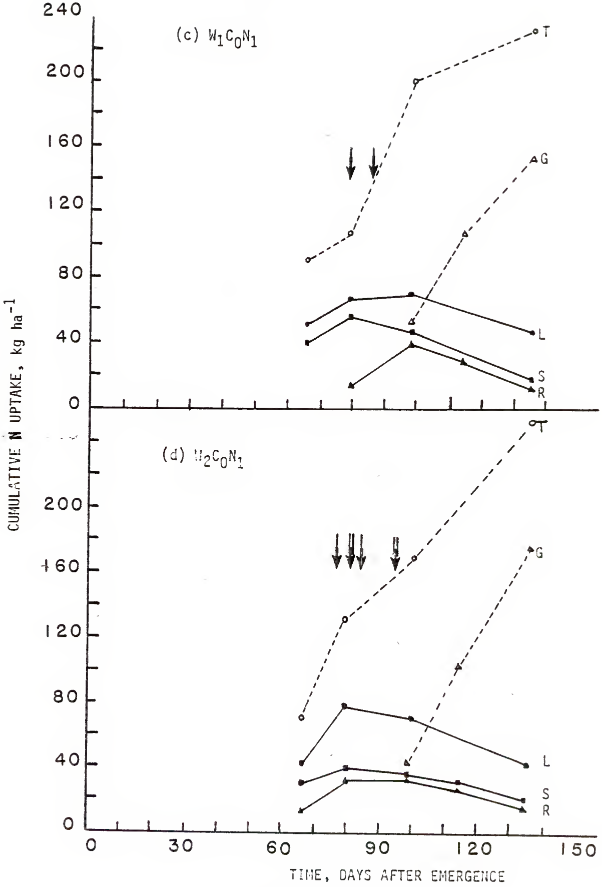


Fig. 4-8---Continued

the findings of Chandler (1960), Hanway (1962b), Kissel and Lagland (1967), Watts and Hanks (1978) and recently by Mutti (1984).

Cumulative plant N uptake is illustrated on Fig. 4-9a. Variable cumulative N uptake values were observed for treatment $W_2C_0N_0$ and $W_1C_0N_1$. This can be attributed to experimental errors and the overall variable crop performance during the 1983 growing season. Also, at harvest, only one plant sample was collected from each treatment. However, the variable cumulative N uptake values are also reflected in the variable grain yield data (Table A2-6, Appendix 2). The data of Mutti (1984) (Fig. 4-9b), who introduced vegetative soil-water stress, also indicate reduced N uptake patterns in response to water and N stress.

Low nitrogen plots had taken up between 25 and 38% of the total N accumulated at harvest by the time of silking (3rd sampling, 80 days after planting). Similar values for the high N treatments range from 46 to 50%. These values can be compared with the data of Hanway (1962b) who reported that by silking time the corn plants had taken up 65% of the total N accumulated throughout the growing season. The smaller values for the low nitrogen treatments can be explained by observing that this treament was designed to induce N stress conditions during the vegetative growth stages (resulting in reduced N uptake). Also by silking time, the 4th N application (applied 98 days after planting) had not yet been applied. The lower values in the high N plots, compared to the 65% reported by Hanway (1962b), are perhaps due to differences in varieties, fertilizer rates and amounts, and several other factors that influence N uptake, assimilation and translocation in the plant.

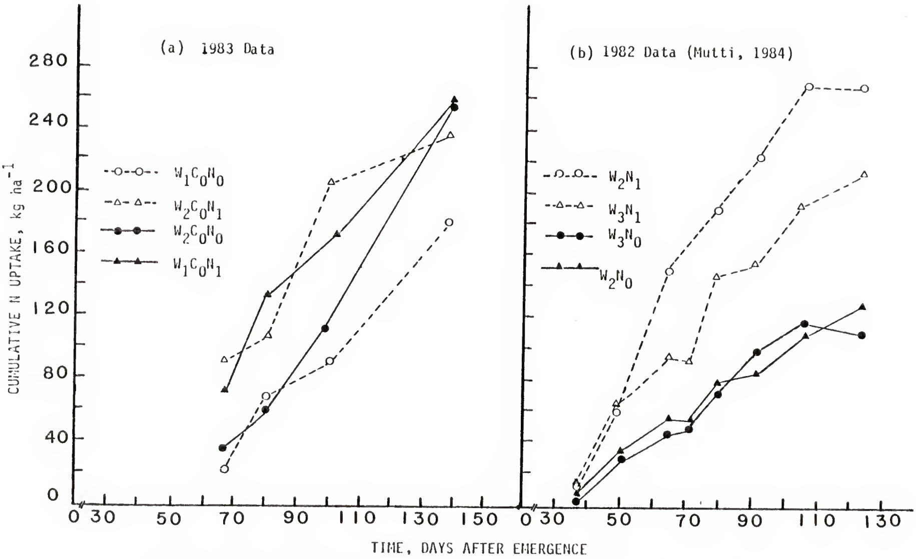


Fig. 4-9 Nitrogen Accumulation in the Whole Plant During the Growing Season

At harvest, the average value of total N uptake was about 266 kg N ha^{-1} in the optimum irrigation (W_2) plots that had sufficient nitrogen (N_1). For the same variety, (McCurdy 84aa), Mutti (1984) reports a mean maximum N uptake value of 269 kg N ha^{-1} under similar fertility and water management conditions. However, Obreza (1983) reports some N uptake values that are more than 300 kg N ha^{-1} for Pioneer Brand 3369A.

Dry Matter Accumulation and Grain Yields

Dry matter yield is presented in Appendix 2 (Table A2-4). Dry matter accumulation in all plant parts parallels that of N accumulation. This is a consequence of cumulative N uptake values being computed from the corresponding dry matter yield (Chandler, 1960; Hanway, 1962a).

Grain yield data are presented on Table A2-6 (Appendix 2). Large grain yield differences are observed between the different treatments in the various replicates. Statistical analysis of the data indicated that the difference in grain yield between W_0 and W_1 was not statistically significant, while W_2 yielded significantly different from both W_0 and W_1 (Duncan Multiple Range Test, DMRT, $P = 0.05$). All treatments were affected by mid-day vegetative stress soil-water conditions, while the imposed reproductive stress affected W_0 and W_1 only. Since W_0 and W_1 did not yield significantly different from each other, it can be concluded that soil-water stress conditions during the reproductive growth stages significantly contributed to decreased grain yield more than any other crop production variable. Reduced amounts of available soil-water in the root zone limit both N and water uptake which are required in large quantities during the reproductive growth stages.

After a two week soil-water stress period, W_1 was provided with sufficient soil-water conditions. But this did not significantly increase the grain yield above W_0 (Rainfed treatment). Hence, it can also be concluded that (i) damage caused by reproductive soil-water stress tends to be of a permanent nature and (ii) reproductive stress periods of two or more weeks have serious irreversible damaging effects on grain yield. These observations are in general agreement with the results of earlier workers. Robins and Domingo (1953) reported reduced grain yield when profile soil-water had reached the lower limit of availability during the reproductive growth stages, while Bennett and Hammond (1983) have demonstrated that small duration soil-water stressing conditions during the vegetative growth stages are of little consequence on the final grain yield.

The grain yield data presented here can be compared with that of Mutti (1984) (Table 4-4). The data in Table 4-4 indicate that higher yields were realized in 1983 compared to 1982. In both years high N plots yielded more than low N plots. Small differences in grain yields were observed between sufficient soil-water and optimum nitrogen treatments in both years. On the other hand, the rainfed treatment in 1983 (under both low and high N) yielded twice as much as the 1982 rainfed treatment. These large differences can be attributed to differences in the rainfall distribution patterns during these years, since N_0 and N_1 were chosen to produce vegetative water stress and optimum N conditions, respectively, in both years. Longer duration stressing soil-water conditions were experienced in 1982 compared to 1983.

Table 4-4 Comparison of grain yield data between 1982 (vegetative water stress) and 1983 (reproductive water stress) at IREP, Gainesville, Florida

1982*		1983	
Treatment	Yield,	Treatment	Yield
	-- kg ha^{-1} --		-- kg ha^{-1} --
Rainfed (W_1N_0)	3466	Rainfed (W_0N_0)	5733
Vegetative water stress (W_3N_0)	7185	Reproductive water stress (W_1N_0)	5843
Optimum irrigation (W_2N_0)	7101	Optimum Irrigation (W_2N_0)	7670
Rainfed (W_1N_1)	3021	Rainfed (W_0N_1)	6046
Vegetative Water Stress (W_3N_1)	9806	Reproductive Water Stress (W_1N_1)	7478
Optimum irrigation (W_2N_1)	12287	Optimum irrigation (W_2N_1)	11662

* Data of Mutti (1984).

The vegetative water stress treatment in 1982, yielded more than the reproductive water stress treatment in 1983, irrespective of the N level. In 1983, the optimum irrigation treatment (W_2) yielded 56% more than the reproductive stress water treatment (W_1) under high nitrogen conditions. Under low nitrogen conditions W_2 yielded 30% more than W_1. Corresponding data for the 1982 growing season are 25% and 1% under high and low nitrogen conditions, respectively. This again illustrates the importance of the time when the stress occurs. More yield loss is expected when stress occurs during the reproductive growth stages compared to the other stages of growth (Robins and Domingo, 1953).

The grain yield difference between subsoiled and conventionally tilled plots were not statistically significant under the 1983 experimental conditions. This is because the subsoiling treatment was not deep enough to break the plow layer as explained in earlier sections. Thus other factors (among which are water and nitrogen) were more important in determining grain yield compared to subsoiling. Corn (McCurdy 84aa) root studies carried out at IREP by Persad (1982) and Riestra-Diaz (1984) have indicated that although the bulk of the root system is concentrated within the top 30 cm depth, some roots were able to penetrate up to 120 cm. Thus, despite rapid N leaching in these sandy soils, the few roots at the deeper depths, were perhaps efficient in extracting the N required by the growing corn plant. Burns (1980) demonstrated that even if less than 15% of the roots are exposed to the N pool, they are able to extract enough N to meet the crops requirement.

It should be recognized that since the 1983 soil-water stressing conditions were of shorter duration, beneficial effects of subsoiling are not observed. Since 1982 had a more erratic rainfall distribution pattern with longer periods of soil-water stress, subsoiling could perhaps have been of benefit. Stressing soil-water conditions facilitate more deep rooting resulting in water and nutrient extraction from deeper soil layers.

Corn Grain Yield vs N Uptake

The relationship between grain yield and N uptake is illustrated on Fig. 4-10. The data from the work of Fischbach et al. (1977), Obreza and Rhoads (1984) (personal communication)and Mutti (1984) are also depicted on the same graph.

There is a wide scatter of data points that defies a unique mathematical relationship between yield and N uptake. This scatter perhaps indicates that not all the N taken up by the plant is directly used in grain formation. Thus, other sinks of N in the plant are equally efficient in utilizing N. Also luxury N uptake takes place in excessively fertilized plots. Depressed N uptake values are associated with stressed soil-water and/or nitrogen treatments, while increased N uptake values are associated with optimum nitrogen and soil-water treatment conditions. The data presented by Obreza (1983) have indicated that Pioneer Brand 3369A shows little grain yield response when N uptake values exceed 150 kg N ha^{-1}.

Obreza and Rhoads (1984) (personal communication) were able to fit the following expression to their data:

$$Y = 172\ (1 - (\exp-(0.0045X))) \qquad (4\text{-}1)$$

where Y is the grain yield (q ha^{-1}) and X is plant N uptake (q ha^{-1}). However, a function of the form:

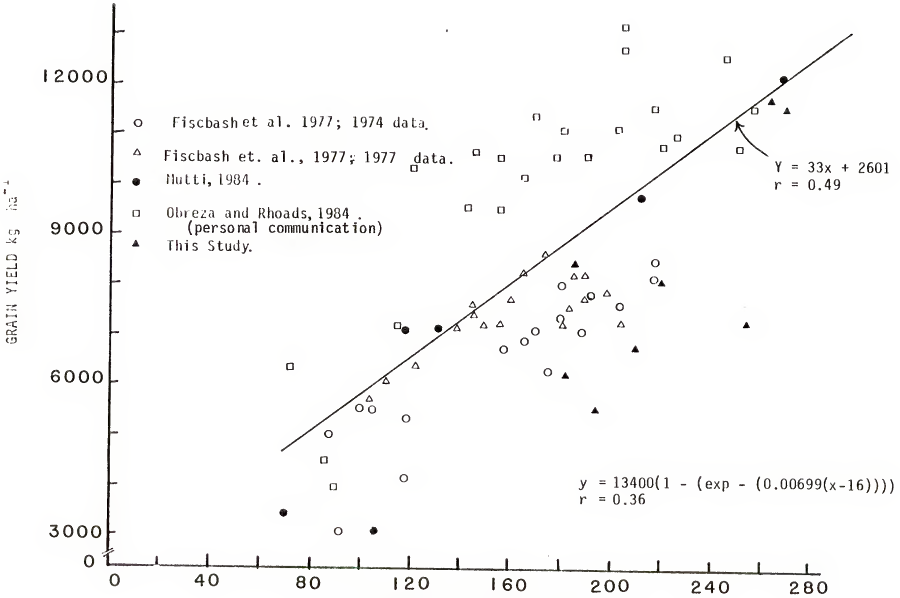


Fig. 4-10 The Relationship Between Grain Yield and Plant N Uptake

$$Y = Y_{max} (1 - (\exp(-b(X-X_0)))) \qquad (4-2)$$

seems more appropriate for both the data of Obreza and Rhoads (1984) and all the data points presented on Fig. 4-10. Where Y_{max} is the maximum grain yield and X_0 is the minimum amount of N that must be taken up by the plant for dry matter production before any grain can be produced and b is a constant. The data in Fig. 4-10 were fitted to equation (4-3):

$$Y = 13400 (1 - (\exp(-0.00699 (X-15.5)))) \qquad (4-3)$$

A linear fit ($Y = MX + C$) to the data was also attempted, where Y is the grain yield (kg ha^{-1}), M is the slope of the line, X is the cumulative N uptake (kg ha^{-1}) and C is the Y intercept (kg ha^{-1}). Values of $M = 33$, $C = 2601$ were obtained, indicating that 2601 kg ha^{-1} grain yield can be realized without cumulative corn N uptake. Thus, the linear function is only valid in the domain of experimentally observed data.

Nitrogen Use Efficiency (NUE)

Nitrogen use efficiency values for high and low nitrogen treatments range between 56 and 64%, and between 104 and 148%, respectively (Table 4-5). The data indicate better nitrogen use efficiency under low N fertility conditions compared to high nitrogen fertility conditions. The particularly high value of 148% for treatment $W_2C_0N_0$ is probably in error because the cumulative N uptake value of 248 kg N ha^{-1} is too high for low nitrogen fertility conditions (168 kg N ha^{-1}) as previously discussed. Generally, these results indicate that nitrogen was not the only determinant of yield, but that other crop production variables were also important under the present experimental conditions. Also, a possible luxury N uptake can contribute to reduced NUE values.

Table 4-5 Average grain yields, cumulative N uptake and nitrogen use efficiency (NUE) in different treatment combinations at IREP, Gainesville, Florida, 1983

	Treatments							
	$W_1C_0N_0$	$W_1C_0N_1$	$W_2C_1N_0$	$W_2C_1N_1$	$W_2C_0N_0$	$W_2C_0N_1$	$W_1C_1N_0$	$W_1C_1N_1$
	kg ha^{-1}							
Mean Grain Yield	5482	8113	8477	11584	6862	11741	6204	6843
N Uptake	176	253	182	265	248	232	208	266
	%							
NUE	105	62	108	64	148	56	124	64

CHAPTER 5

SIMULATION OF WATER AND NITROGEN DYNAMICS UNDER IRRIGATED CORN - GAINESVILLE STUDY

Root Zone Soil-Water

Measured and simulated total soil-water in the root zone (0 - R(z,t)) during the growing season are compared in Fig. 5-1a through Fig 5-1d. The data for both subsoiled and conventionally tilled plots are presented on the same graph. Model parameters used in present simulation studies are presented in Appendix 3 (Table A3-1). Generally, good agreement between measured and predicted results were found except for one sampling date, May 11, 1983 (62 days after planting). This measured value is probably in error because soil sampling was done soon after 2.2 cm of rain after a period of 5 days without rain. If this value can be neglected, we can conclude that the model tracked stored root zone water very well. The lines labelled θ_{fc} water and θ_{15} water are field capacity soil-water and wilting point soil-water residing in the corn root zone during the growing season. The corn root zone increased with depth and time. It was 0 cm at planting and reached a maximum depth of 105 cm approximately 99 days after planting. Earlier, Rao et al. (1981) used the field data of Hammond et al. (1981) where they also observed good agreement between measured and predicted stored profile water. Similar results were obtained by Riestra-Diaz (1984). Because of this confidence in the model results, the rainfed treatment was also simulated (Fig. 5-1e) though measured data for this treatment were unavailable.

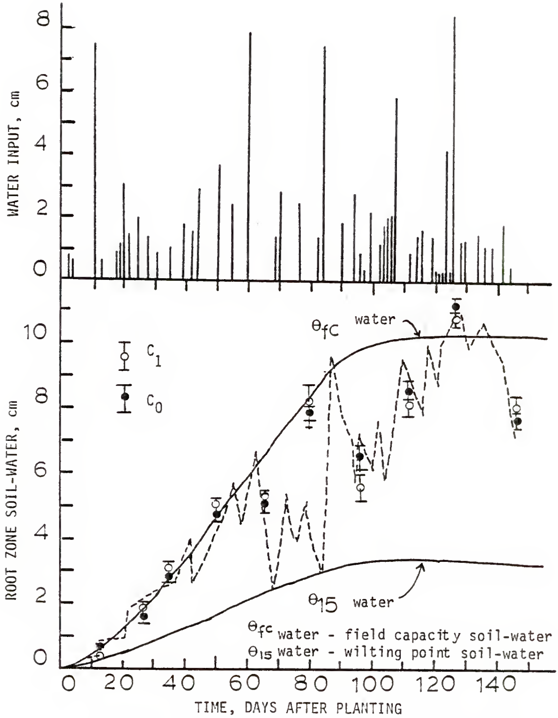


Fig. 5-1 Comparison Between Measured and Predicted Total Amounts of Water in the Corn Root Zone During the Growing Season, (a) W_2N_0

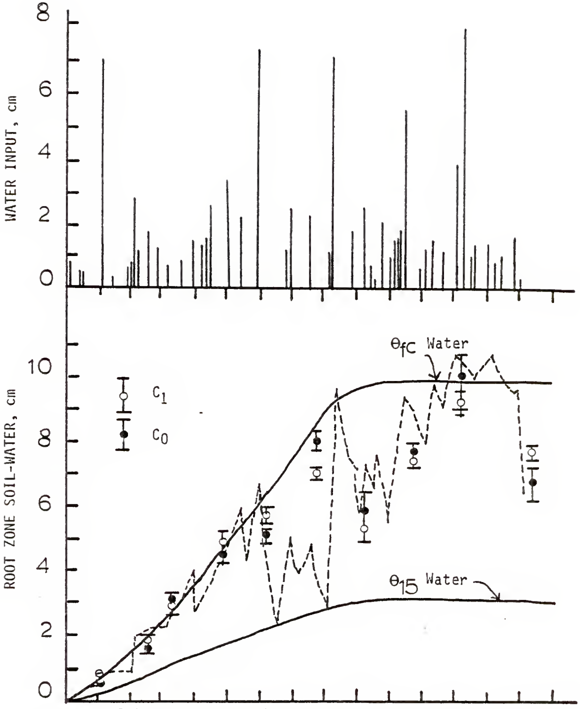


Fig. 5-1---Continued, (b) W_2N_1

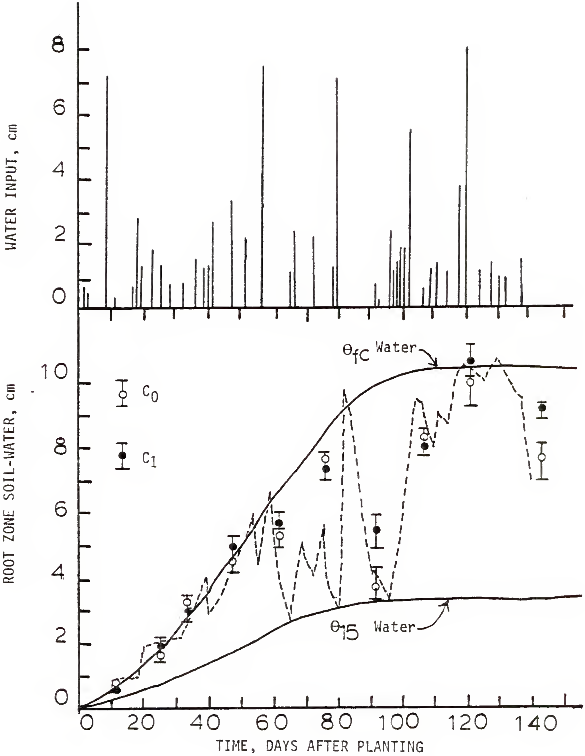


Fig. 5-1---Continued, (c) W_1N_0

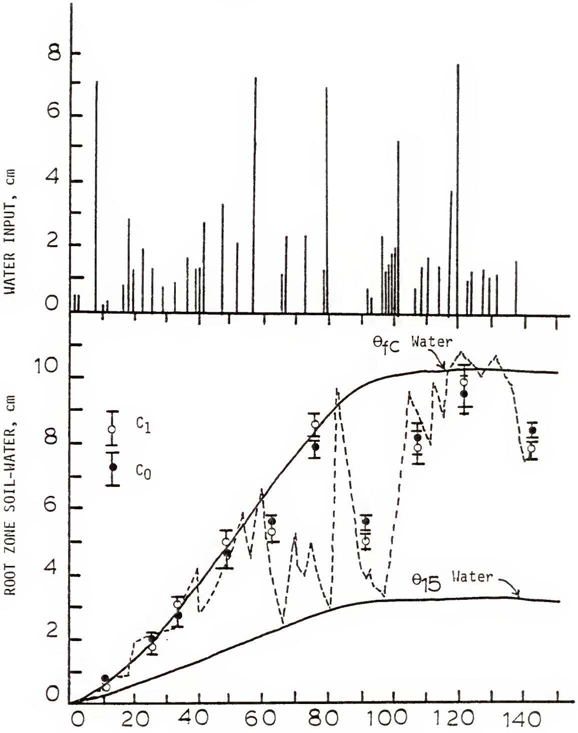


Fig. 5-1---Continued, (d) W_1N_1

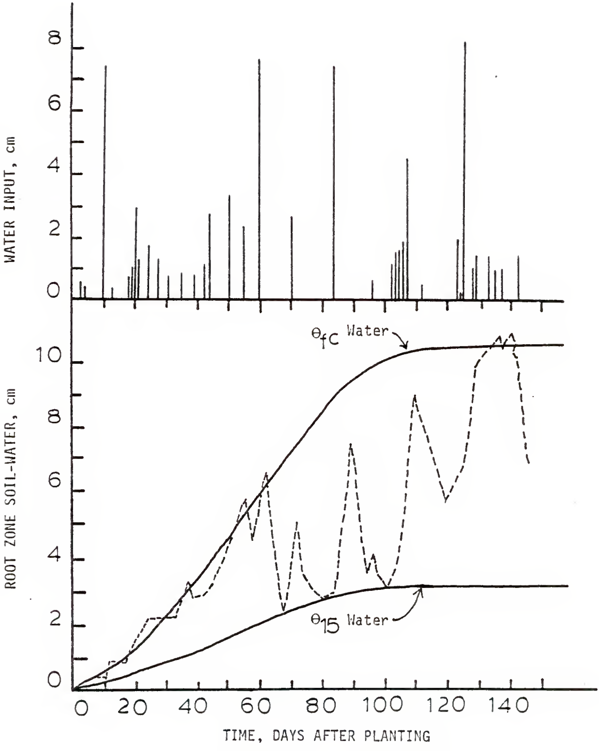


Fig. 5-1---Continued, (e) W_0

Similar results were obtained when measured stored profile water was compared with simulated results (data not shown).

Soil Nitrogen

Predicting Solute Peak Positions

Measured and simulated solute peak positions for $W_1C_0N_0$, $W_1C_0N_1$, $W_2C_0N_0$ and $W_2C_0N_1$ are compared in Fig. 5-2a through Fig 5-2d. Similar trends were observed for subsoiled plots. Data are presented for individual replicates because of large variability in the observed solute leaching patterns. The model predicted lines represent multiple NO_3^--N peaks resulting from 4 and 5 split applications in the low and high fertility plots, respectively.

The data for $W_1C_0N_0$ (Fig. 5-2a) show satisfactory agreement between model simulations and measured data. The simulated values in most cases overestimated the solute peak positions. No discernable solute peak positions could be identified after the fourth application (98 days after planting). This is because of repeated rainfall events that occurred for six consecutive days (including an irrigation of 2.54 cm) starting 99 days after planting. Differential leaching between replicates is reflected in the different solute peak positions in the treatments under consideration.

Under high nitrogen conditions (Figs. 5-2b and 5-2d), model simulations are in satisfactory agreement with measured peak positions, except for the last sampling date (data not shown). The model predicted rapid N leaching, while measured solute peaks were found near the surface. Non-uniform N applications, soil spatial variability, non-uniform N uptake patterns and non-uniforn soil surface boundary

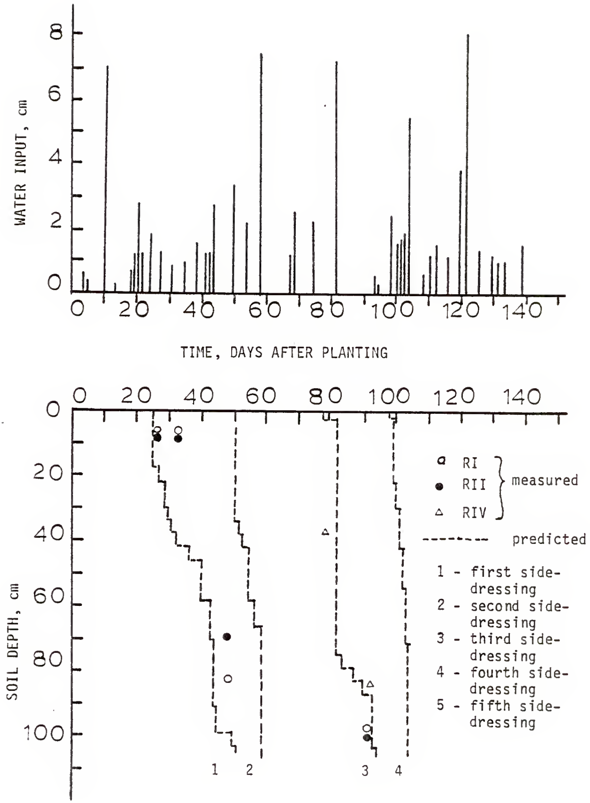


Fig. 5-2 Comparison Between Measured and Predicted Solute Peak Locations During the Growing Season, (a) $W_1C_0N_0$

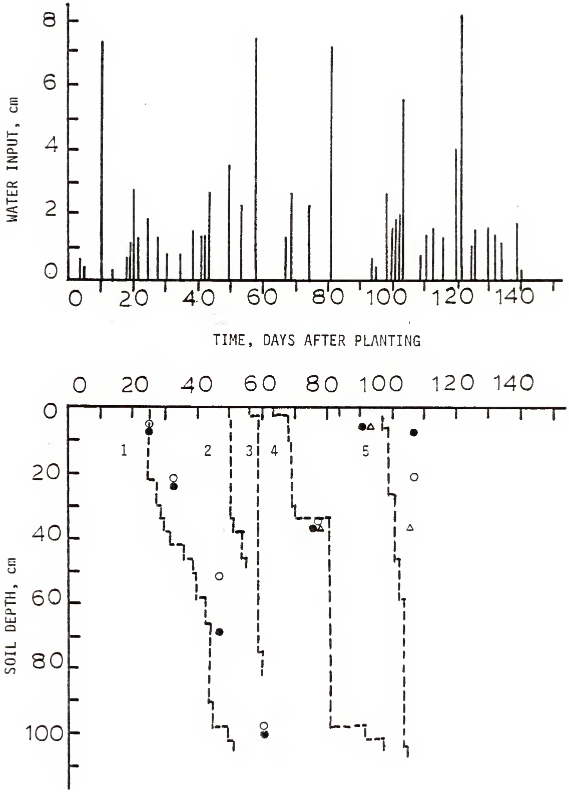


Fig. 5-2---Continued, (b) $W_1C_0N_1$

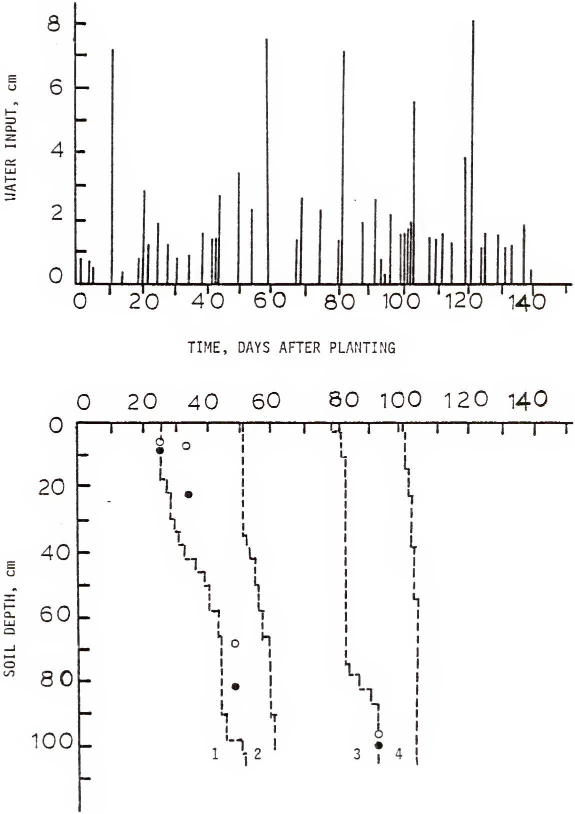


Fig. 5-2---Continued, (c) $W_2C_0N_0$

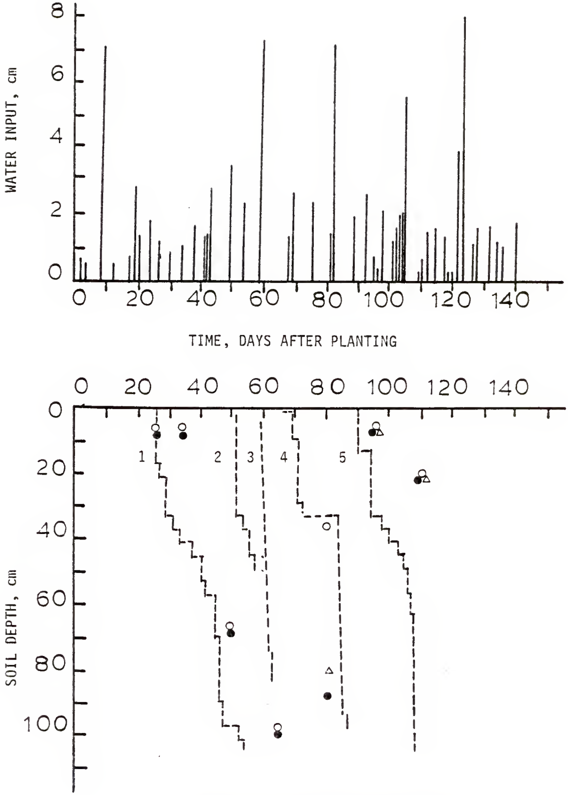


Fig. 5-2---Continued, (d) $W_2C_0N_1$

conditions caused by variable rainfall and/or irrigation inputs, as explained in Chapter 4, equally influenced the advance of NO_3^--N peak positions.

The present data can also be compared with earlier simulation studies. Rao et al. (1977) reported close agreement between measured and simulated Cl^- leaching peak positions in an actively growing millet field. Similar satisfactory results have been obtained for aldicarb nematicide leaching (Rao et al., 1983; Bilkert, 1984) under Florida sandy soils. Rose et al. (1981, 1982) verified the applicability of the PDM using lysimeter data. They observed close agreement between measured and simulated results. In another recent study, Smith et al. (1984) have compared the predicting ability of the Burns model (Burns, 1975) and the PDM as previously presented by Levin (1964). They found that the PDM overpredicted the solute peak front by 30% compared to the Burns model.

Considering the approximating assumptions embedded in NITROSIM model and the difficult nature in characterizing nitrogen behavior under field conditions (even under situations where the soil profile is assumed to be homogeneous as in Florida sandy soils) the model simulations presented here can be considered satisfactory. It is anticipated that better agreement between model simulations and measured data can be obtained if more frequent soil samplings are made after each major rainfall/irrigation event.

Integral Amounts of NO_3^--N in the Soil Profile (0-105 cm)

Measured and simulated amounts of NO_3^--N residing within the soil profile (0-105 cm) during the growing season are compared in Fig. 5-3.

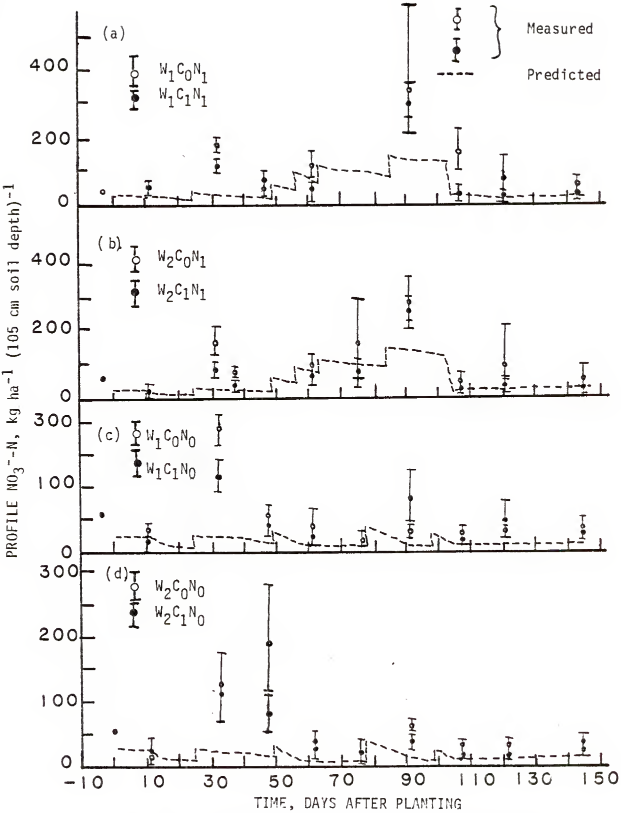


Fig. 5-3 Comparison Between Measured and Predicted NO_3^--N Total Masses in the Soil Profile (0-105 cm) During the Growing Season

Because of the large quantities of NO_3^--N that were observed in soil samples that were collected on the band, three sets of simulations were made (i) one using the nominal rate of N application and (ii) two others using recalculated rates that were, respectively, 6 and 8 times larger than the nominal N application rate.

The nominal N application rate predicted masses indicate that the model generally underpredicted the total masses in the soil profile. Considering the fact that the solute transport submodel in NITROSIM is essentially the PDM the observed results are expected. NITROSIM will tend to overestimate the total amount of mass leaving the soil profile, resulting in less stored total masses in the soil profile; hence the underprediction. At other times the model overestimated the total masses.

Under low nitrogen conditions, similar patterns were observed (Fig. 5-3c,d). However, serious underpredictions were observed on the 33rd, 48th and the 92nd day after planting. The recalculated rates that were 6 times the nominal N application rates predicted values that were reasonably closer to the measured values 33 and 48 days after planting, respectively (data not shown). Recalculated rates that were 8 times the nominal rate of N application resulted in predicting large integral amounts of NO_3^--N in all cases, except when soil sampling was carried out on the day of N application (e.g., March 21, 1983).

The inability to sample on the band produced low values of total masses in the soil profile. However, when soil sampling was done on the band, large masses were calculated (e.g., data for March 21, 1983, the values of which are not shown on the graphs). On average, therefore, the observed total masses were within those that could be predicted by the model . The summing and the averaging schemes used, despite the large range values, tend to produce results that are within those that can be predicted by the model. However, to get representative mean values a large number of samples is required which is labor prohibitive.

Integral Amounts of NH_4^+-N in the Soil Profile (0-105 cm)

Figure 5-4 compares measured and predicted NH_4^+-N total masses in the soil profile. Again recalculated rates produced high values that were far removed from measured data. The nominal N application rates produced data values that were in fair agreement with those measured in the field, although the model predictions underpredicted the measured values.

NH_4^+-N total masses exhibit a distinct linear loss patterns following each N application. This can be explained by observing that NH_4^+-N in the soil profile is always either transformed to NO_3^--N or taken up by plant roots. Again average values of total masses residing in the soil profile proved to be the best estimator of nitrogen changes under heterogeneous field conditions.

Plant Nitrogen Uptake

Figure 5-5 compares measured and predicted N uptake values. The data indicate close agreement between predicted and measured data values. Better agreement is observed under the high nitrogen fertility level compared to the low nitrogen fertility level. The model simulations tracked reduced N uptake under stressing soil-water and/or nitrogen conditions fairly well (Fig. 5-5c,d). Under optimum soil-water and/or nitrogen conditions N uptake followed more closely to the maximum demand

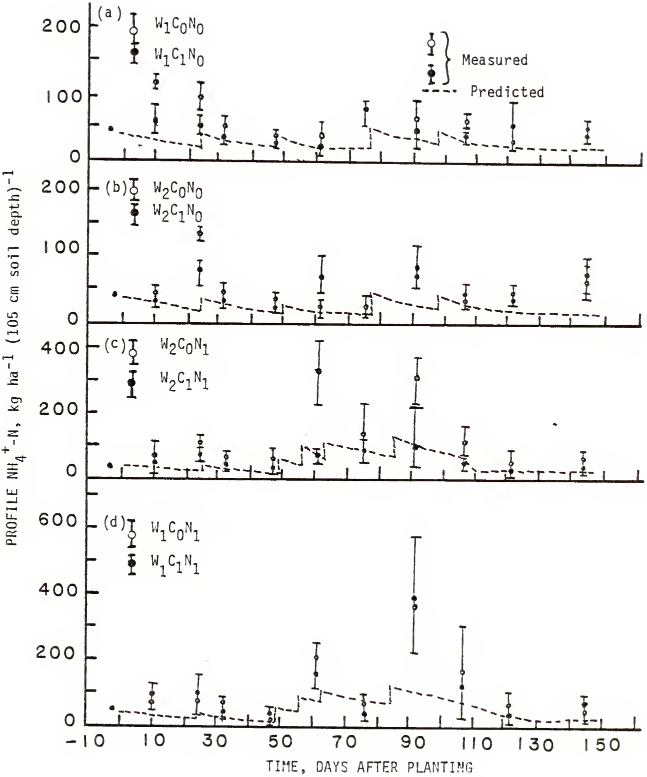


Fig. 5-4 Comparison Between Measured and Predicted NH_4^+-N Total Masses in the Soil Profile (0-105 cm) During the Growing Season

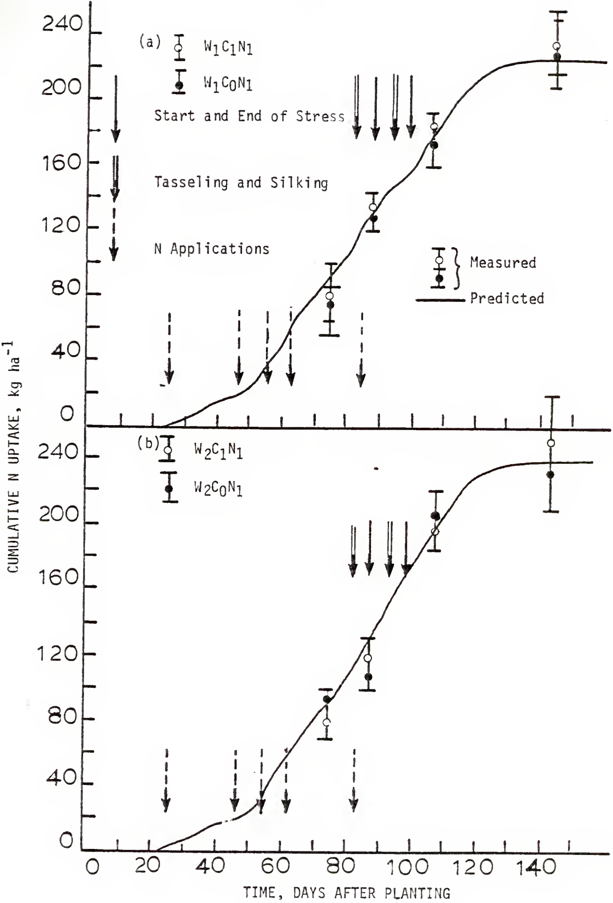


Fig. 5-5 Comparison Between Measured and Predicted Cumulative N Uptake During the Growing Season

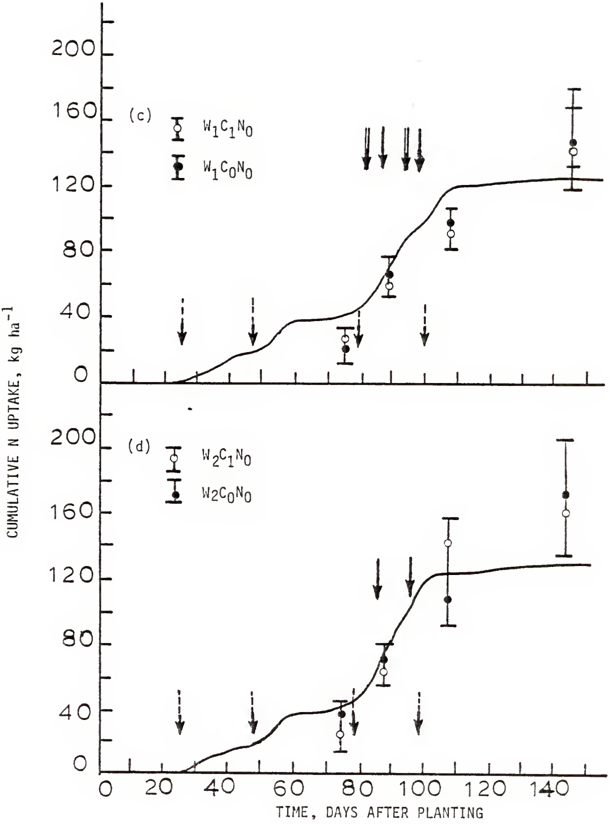


Fig. 5-5---Continued

function (Fig 5-5a,b). Model simulations for W_1, however, show continued increase in N uptake despite the damaging reproductive stress water conditions. Mutti (1984) ascribed unsatisfactory agreement between measured and simulated results in low nitrogen and water treatments to the fact that the current version of NITROSIM does not account for irreversible and/or cumulative effects of water and nitrogen stress on corn growth.

In all treatment combinations lack of fit was observed with the harvest N uptake values. Such variability is also correlated with the variable grain yield data (Appendix 2, Table A2-6). A second reason can be attributed to the fact that only one plant was sampled from each treatment combination at harvest compared to other sampling dates when two plants were collected. This is because it was impractical to sample two huge corn plants under the present circumstances.

However, these results in conjunction with those of Mutti (1984) clearly indicated that NITROSIM can be used to predict plant N uptake with a good level of accuracy.

Water and Nitrogen Balance Sheets

Measured and predicted water and nitrogen balance sheets are compared in Table 5-1 and Table 5-2. Initial and final total amounts of water stored in the soil profile (Table 5-1) indicate good agreement between model simulated and measured values. The model overestimated cumulative drainage under all treatment combinations. The error identified in measured profile soil-water can equally be identified as contributing to these differences.

The nitrogen balance sheet shows poor agreement between model simulations and measured data. Negative measured values were obtained in all low N fertility plots. This indicates nitrogen gain into the system under study, compared to N loss beyond the maximum root zone (105 cm) in high N fertility plots. N uptake beyond the 105 cm depth can contribute to this gain. However, the problem associated with soil sampling, non-uniform N application and soil spatial variability appear to be the main factors contributing to the lack of agreement between measured and predicted values.

Table 5-1 Measured (M) and predicted (P) balance sheets for water in the soil profile (0-105 cm) at the end of the growing season at IREP, Gainesville Florida, 1983

	Treatments							
	W_1N_0		W_1N_1		W_2N_0		W_2N_1	
	M	P	M	P	M	P	M	P
	cm							
Water Input	95.5	95.5	95.5	95.5	98.8	98.8	98.8	98.8
Initial Profile H_2O	9.2	9.5	8.5	9.5	9.0	9.5	8.4	9.5
Final Profile H_2O	8.1	7.2	8.4	7.2	8.1	7.1	7.5	7.1
Seasonal ET	52.0*	52.0	52.0*	52.0	54.9*	54.9	54.9*	54.9
Seasonal Drainage	44.6	45.8	43.6	45.8	44.8	46.3	44.8	46.3

* Seasonal ET was not measured and was set equal to that predicted by the model simulations.

Table 5-2 Measured (M) and predicted (P) balance sheet for nitrogen in the soil profile (0-105 cm) at the end of the growing season at IREP, Gainesville, Florida, 1983

	Treatments							
	W_1N_0		W_1N_1		W_2N_0		W_2N_1	
	M	P	M	P	M	P	M	P
	kg ha^{-1}							
Fertilizer Input	168	168	413	413	168	168	413	413
Initial N	89	73	89	73	89	73	89	73
Mineralized N*	30	3	30	3	30	3	30	3
Final N	117	12	124	13	92	12	99	13
N uptake**	212	124	286	233	237	124	274	233
N leached	-32	108	122	243	-42	108	159	243

* Mineralized N (30 kg N ha^{-1}) was not measured but derived from earlier studies (Rao et al., 1981).

** Following the work of Watts and Hanks (1978), underground cumulative N uptake was assumed to be 10% of the above ground cumulative N uptake.

CHAPTER 6

CHARACTERIZATION OF SOIL PROPERTIES AND SIMULATION OF NITROGEN DYNAMICS UNDER RAINFED CONDITIONS - MALAWI STUDY

Characterization of Soil Properties

Soil Physical Characteristics - Laboratory Studies

Soil-water constants (θ_s, θ_{fc} and θ_{15}) for Chitedze, Lisasadzi, Mbawa and Lunyangwa are presented on Table 6-1, where θ_s, θ_{fc} and θ_{15} represent infiltration, field capacity and wilting point soil-water contents, respectively. The data for θ_{fc} and θ_{15} indicate a narrow range of total available water capacity (AWC = $\theta_{fc} - \theta_{15}$) in these soils. The values of θ_{fc}, θ_{15} and θ_s were obtained at 1/3 bar (333 cm of H_2O), 15 bar (1500 cm H_2O) and 0 bar (0 cm of H_2O), respectively. These results are in agreement with previous data (Saka, 1979; unpublished data). They are also in general agreement with data obtained from other tropical areas reported by Lal (1978) for some Nigerian soils, Wolf and Drussldolf (1970) for some Puerto Rican Oxisols, and McLean and Yager (1972) for some Zambian soils.

Saturated soil-water contents indicate that larger values are associated with the better aggregated fine textrued soils at Lunyangwa, as compared to the less well aggregated coarse textured soils at Lisasadzi and Mbawa.

Soil-water release curves for Lisasadzi, Mbawa and Lunyangwa for the 0-6, 15-30 and 30-36 cm soil depth increments, are depicted in Fig. 6-1.

Table 6-1 Physical characteristics of some selected Malawi soils

Location	Depth	ρ_b*	θ_{15}	θ_{fc}	θ_s	K_s
	-cm-	-g cm^{-3}	--------	cm^3 cm^{-3}	-------	-cm hr^{-1} -
Lunyangwa (Uncultivated soil)	0-15	1.3	0.03	0.36	0.43	2.0
Lunyangwa (Uncultivated soil)	15-30	1.3	0.20	0.29	0.43	0.8
Lunyangwa (Cultivated Soil)	0-15	1.2	0.10	0.40	0.54	52.0
Lunyangwa (Cultivated soil)	15-30	1.3	0.20	0.30	0.40	5.2
Mbawa-1	0-15	1.4	0.20	0.16	0.30	34.9
Mbawa-1	15-30	1.5	0.19	0.15	0.29	15.5
Mbawa-2	0-15	1.6	0.20	0.31	0.40	2.9
Mbawa-2	15-30	1.5	0.22	0.30	0.39	3.7
Lisasadzi	0-15	1.4	0.03	0.16	0.36	29.8
Lisasadzi	15-30	1.4	0.03	0.11	0.32	18.3
Chitedze **	0-30	1.2	0.17	0.23	0.55	3.5

* ρ_b - soil bulk density, K_s - saturated hydraulic conductivity.

** - The value of θ_s was not measured for the Chitedze site, but calculated frombulk density (1.2 g cm^{-3}) and particle density (2.64 g cm^{-3}) for the Lilongweseries.

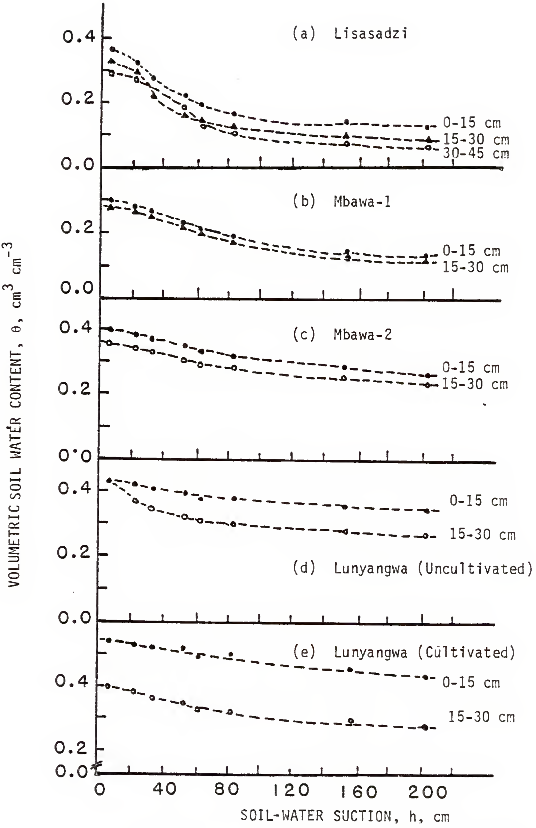


Fig. 6-1 Soil-Water Characteristic Curves for Mbawa, Lunyangwa and Lisasadzi

These data reveal a slow release of soil-water with increasing suction at all sites. There are generally small differences in soil-water release characteristics for soil cores from different depths (which means that the data can be pooled into one soil-water release curve) except for the soil cores from Lunyangwa. The cultivated soils at Lunyangwa tend to retain more water in the surface horizons compared to the subsurface horizons. This is probably due to the influence of cultivations, the addition of organic matter (in the form of cattle manure) and the well aggregated nature of these fine textured soils.

Saturated hydraulic conductivity values are also presented on Table 6-1. Relatively high values were obtained for Lisasadzi, Mbawa-1 and the cultivated soil at Lunyangwa. Higher values for Lunyangwa are not particularly surprising considering the fact that Lunyangwa receives an annual average rainfall of 138 cm (with 86% of the rain falling between November and April) with little runoff. This is because the soils are deep, friable and well aggregated resulting in good water transmitting characteristics. High values at Lisasadzi and Mbawa-1 are due to the coarse textured nature of these soils. Low values for the Mbawa-2 are probably caused by clay accumulation in the B horizon (argillic horizon; Appendix 1, Table A1-2). Natural compaction, due to the undisturbed nature of the Lunyangwa uncultivated soils, is probably the main cause of decreased K_s values at this site.

Hydraulic conductivity functions for Mbawa-1 and Lisasadzi soils are illustrated in Fig. 6-2a. These $K(\theta)$ relationships demonstrate an exponential decrease in K as θ is reduced. Soil bulk density values illustrate the differences in total porosity that exists between Lunyangwa, Mbawa and Lisasadzi (Table 6-1). A maximum bulk density

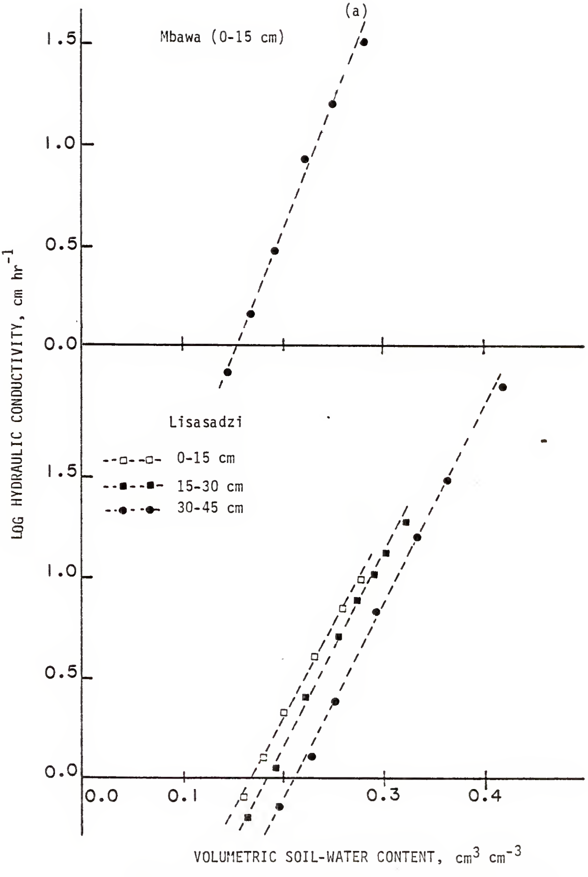


Fig. 6-2 Hydraulic Conductivity as a Function of Volumetric Soil-Water Content for Mbawa-1 and Lisasadzi

(b) Chitedze

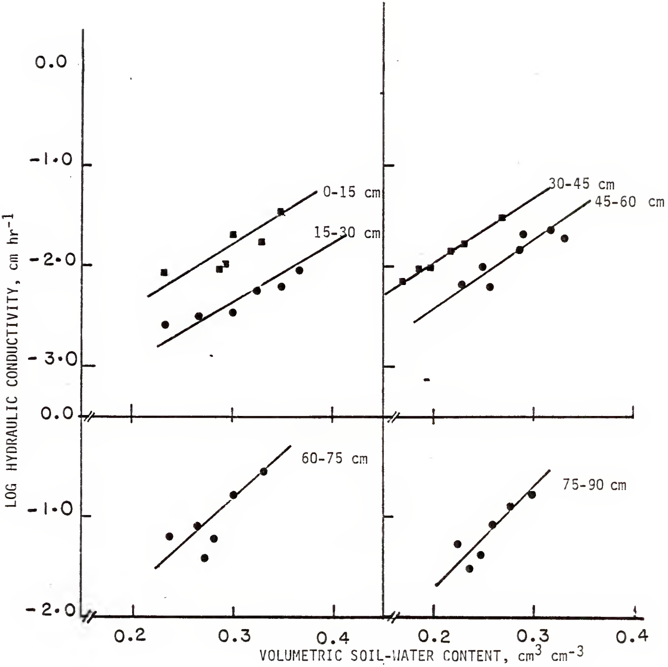


Fig. 6-2---Continued

value of 1.60 g cm^{-3} was observed for the sandy soil at Lisasadzi. Bulk density values in excess of 1.60 g cm^{-3} indicate the presence of lower total porosities and have been reported to restrict root development. However, most of these soils have soil bulk density values that are common for most mineral soils in Malawi.

Soil Physical Characteristics - Field Studies

The measurements from the field experiment at Chitedze were used to calculate $K(\theta)$ functions at various soil depths (Fig. 6-2b). The hydraulic conductivity function used is of the form $\log K(\theta) = b \log\theta + a$, where a and b are constants, while soil-water content data were obtained from soil-water release curves (Fig. 6-3). Comparison with previous data is not possible because data for Malawian soils are currently not available. Nonetheless, these $\theta(h)$ and $K(\theta)$ data were utilized as inputs in the NITROSIM model for simulating nitrogen dynamics under rainfed conditions in Malawi.

Soil Chemical Characteristics

Some soil chemical analysis data are presented on Table 6 soils have a wide range of pH values. The occurence of $CaCO_3$ (A 1, Table A1-1) and the low but variable rainfall pattern (rainfall averages 82 cm per year) contribute to the observed pH values of more than 7.0 at Ngabu.

Lunyangwa has acidic soils (pH less than 5.5). The values reported here are slightly lower than those reported by Mitchell and Ntokotha (1974) (pH range of 5-5.7 and 5-5.9 for the 0-15 and 60-90 cm depth increments, respectively). Generally, pH values are low, at least

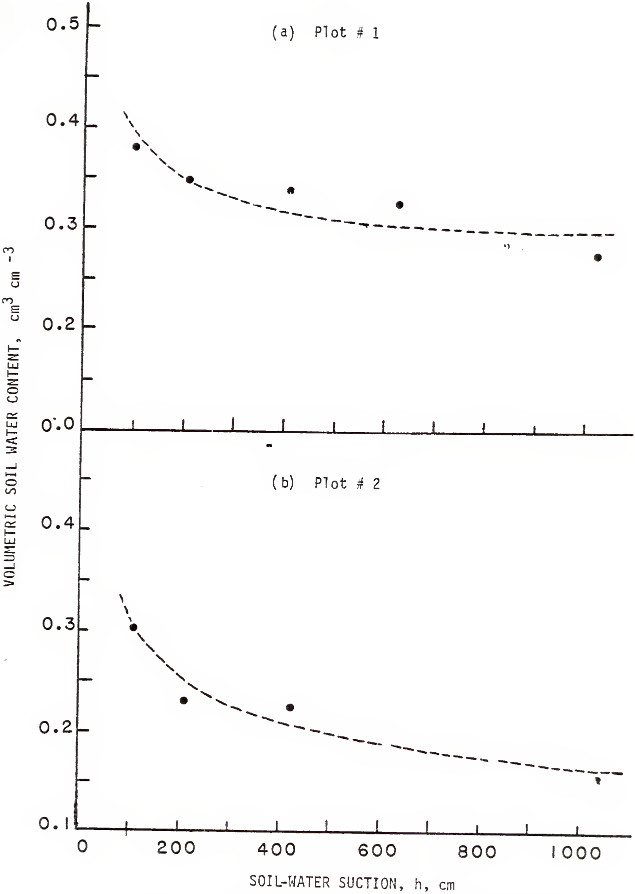


Fig. 6-3 Soil-Water Characteristic Curves for the Lilongwe Series, Chitedze

Table 6-2 Chemical characteristics of some selected Malawi soils

Location	Depth	pH $_{H_2O}$	pH_{KCl}	Δ pH	ZPC
	--cm--				
Ngabu (Field #6)	0-45	8.3	6.9	-1.4	7.4
Ngabu (Black Vertisol)	0-45	8.4	7.0	-1.4	7.4
Ngabu (Brown Vertisol)	0-45	8.4	6.8	-1.6	7.4
Mchinji-Chimwemwe	0-30	7.0	6.1	-0.9	6.5
Salima ADD	0-30	5.6	4.7	-0.9	5.3
Mwanza-Thembani	0-30	5.9	4.1	-1.2	-
Kasinthula Station	0-30	7.0	6.1	-0.9	-
Lunyangwa (Uncultivated soil)	0-15	5.0	4.1	-0.9	4.2
Lunyangwa (Uncultivated soil)	15-30	4.6	4.1	-0.5	4.5
Lunyangwa (Cultivated soil)	0-15	5.0	4.2	-0.8	4.4
Lunyangwa Cultivated soil)	15-30	4.9	4.3	-0.6	4.4
Bulala	0-15	5.7	4.6	-1.1	5.3
Bulala	15-30	5.9	4.6	-1.3	5.0
Mbawa	0-15	6.0	4.8	-1.2	5.3
Mbawa-1	15-30	6.1	4.5	-1.6	4.9
Mbawa-2	0-15	5.8	4.4	-1.4	5.6
Mbawa-2	15-30	6.1	4.6	-1.5	5.6
Eheleni Turn Off	0-15	6.3	4.7	-1.6	5.6
Lisasadzi	0-15	6.3	5.3	-1.0	5.8
Lisasadzi	15-30	6.6	5.3	-1.3	6.0
Chitedze	0-30	6.0	4.9	-1.1	5.8

suggesting the weathered nature of these soils. The pH values from other sites are in between these ranges, which is expected because the annual rainfall totals at these sites are in between those received at either Lunyangwa or Ngabu.

The pH values in 1N KCl (pH$_{KCl}$) and the resulting ΔpH values (ΔpH = pH$_{KCl}$ - pH$_{H_2O}$), indicate that the addition of KCl depressed the soil pH in all these soils. This indicate the presence of negatively charged clay minerals as compared to some tropical soils that exhibit anion exchange characteristics as reported by Uehara and Gilman (1981). In the absence of exchangeable aluminum data, the interpretation of these results is difficult. However, Uehara and Gilman (1981) suggest that if ΔpH values are near zero, then the soil is dominated by variable surface charge clays. Values closer to zero are indicated by the Lunyangwa soils. The higher ΔpH values for the other sites indicate the presence of high negative surface charge density and nothing can be said about the presence of a permanent or a variable surface charge (Uehara and Gilman, 1981). Mwandemere and Robertson (1976) also reported depressed pH values in KCl for all the Malawian soils they studied. However, they report pH values of -0.48 and -0.71 for Lisasadzi and Mbawa, respectively. This indicate the presence of at least some variable charge clay minerals. However, since there are no soils with positive values, it can be safely concluded that these soils have sizeable amounts of weatherable minerals.

Even for the more weathered soils at Lungangwa, Mitchell and Ntokotha (1974) reported the existence of weatherable minerals despite the high acidity.

Values of zero points of charge (ZPC) (Table 6-2) further illustrate that these soils have not attained a soil pH that corresponds to zero net surface charge. Further, the shape of the graphs relating net surface charge (as reflected in the amount of adsorbed H^+ or OH^-) to changes in pH, indicate a near linear relationship near the ZPC, but steeper slopes on either side of this point. Figure 6-4 illustrates this relationship for Lunyangwa, Mchinji and Salima soils. The steep slopes on either side of ZPC are indicative of the high baffering capacity of these soils, especially those with acidic pH values (<5.5).

These results have important implications on the transport of soluble nutrient elements in these soils. The occurrence of a net negative surface charge indicate that the NO_3^--N ion will not be retarded owing to the adsorption/desorption process. The soils at Lunyangwa might slightly retard the transport of the NO_3^--N ion due to the presence of at least some positively charged clay particles. However, studies conducted on some highly weathered tropical soils have indicated the presence of variable surface charge clay minerals in most tropical soils (positive ΔpH values). Balasurbramanian (1973) reported the occurrence of a net positive charge on some Hawaiian Oxisols. Uehara and Gilman (1981) have reported similar results for Puerto Rican and Malaysian Oxisols. Recently, Tissens and Zauyah (1982) have also observed the occurrence of variable surface charge clay minerals on some Malaysian Oxisols.

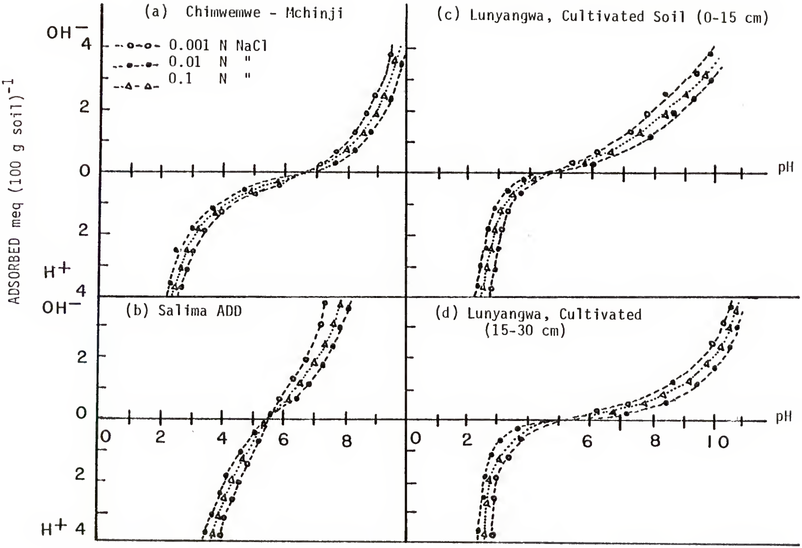


Fig. 6-4 Net Surface Charge as a Function of pH at Different Electrolyte Concentrations for Mchinji, Salima and Lunyangwa

From this study, it can be concluded that most Malawian soils will not retard the movement of NO_3^--N. N fertilizer management is therefore essential for profitable crop production systems and reduced potential for N contamination of groundwater reservoirs.

Other Model Input Data

The rainfall data recorded at Chitedze for the 1952/53, 1967/68 and 1973/74 growing seasons were selected for the present simulation studies because they represent years of low, medium and high rainfall conditions. Table 6-3 presents the monthly rainfall totals for the months of October to May. Detailed rainfall data are given in Table A4-1 (Appendix 4).

Table 6-3 Total monthly rainfall totals for Chitedze, Malawi.

	Month of the Year								
Year	O	N	D	J	F	M	A	M	Totals
	cm								
1952/53	0.00	11.38	23.11	22.68	8.79	12.57	1.14	0.56	80.28
1967/68	0.23	6.58	15.32	20.70	8.10	7.21	4.34	1.07	63.55
1973/74	0.86	4.88	18.77	29.31	21.59	31.80	6.25	9.12	122.58

The value of K_d was not measured but was selected to be 1.0 $cm^3\ g^{-1}$ based on earlier simulation studies. Selim and Iskander (1981) reported that K_d values in the range of 0.05 and 1.5 simulate a wide range of soils having different cation exchange capacities. Later, Iskander and Selim (1981) found that a K_D value of 1.0 and 1.5 described ion exchange adequately for a Windsor sandy clay loam, provided the first order rate kinetic coefficient was chosen to be 0.1 and 0.075 hr^{-1}, respectively.

For Florida sandy soils, Rao et al. (1975) and Rao et al. (1981) have used values of 3.2 and 0.2 cm^{-3} g^{-1} soil, respectively, to describe ion exchange. Tilloston and Wagenet (1980) used a value of 2.8 for a Milville silt loam that had an average CEC of 9.4 meq(100g soil)$^{-1}$ in the 0-120 cm soil depth.

An inflow flux of 2.5 cm hr^{-1} and a redistribution period of 6 days were used based on rainfall intensity and distribution patterns at Chitedze, while the other parameters were chosen based on model stability characteristics and the similarity in weather conditions between Malawi and Florida.

Simulation of Nitrogen Dynamics Under Rainfed Conditions

Predicting Solute Peak Locations

These simulations considered nitrogen transport in a corn field that was planted late November or early December with a 130 day maturity period. In all cases considered, nitrogen (as NH_4NO_3) was applied 25 days after planting (with the exception of the split nitrogen application) at a rate of 224 kg N ha^{-1} that is normally recommended for corn in most parts of Malawi.

Figs. 6-5a, 6-5b and 6-5c illustrate the advance of the solute peak locations for the low (1967/68), medium (1952/53) and high (1973/74) rainfall growing seasons. The solute peak positions did not penetrate deeper than 65 and 84 cm in 1967/68 and 1952/53, respectively. During the wet year of 1973/74, the maximum solute peak penetrated deeper than the 150 cm soil depth 135 days after N application. This signals the danger for nitrate leaching to ground water reservoirs during years of high rainfall.

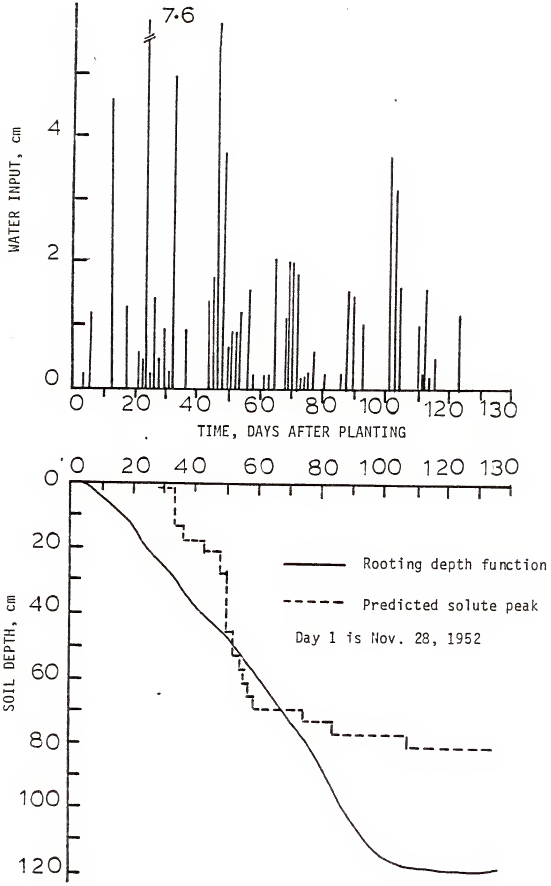


Fig. 6-5 Predicted Solute Front Locations During the Growing Season, Chitedze, (a) 1952/53

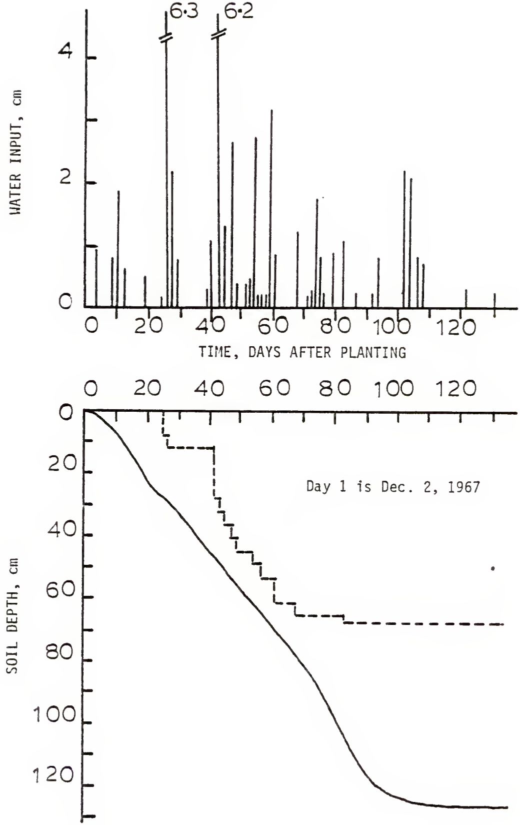
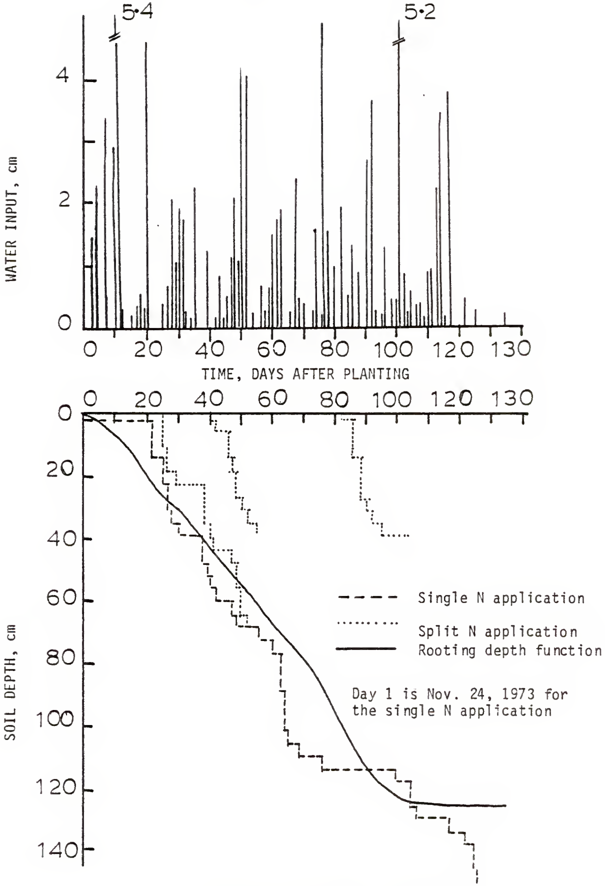


Fig. 6-5---Continued, (b) 1967/68



Day 1 is Nov. 24, 1973 for the single N application

Fig. 6-5---Continued, (c) 1973/74

The maximum depth of leaching can be related to the total rainfall that is received during the period under consideration. Westelaar (1962) working in Australia found a high correlation ($r = 0.946$, $P = 0.01$) between mean movement of applied chloride and total amounts of rainfall during the 1958/59 growing season. The use of total amounts of rainfall can sometimes be misleading, unless the effective amount of water is also known as discussed in Chapter 2.

When three split N applications were made 1, 40 and 80 days after planting for the high rainfall year (1973/74), the solute front positions did not penetrate deeper than 70 cm (Fig. 6-5c). Thus, during wet years split N applications will increase N use efficiency and reduce N leaching by keeping the nitrogen within the root zone.

Simulation studies were not carried out for other stations because the rainfall data for these locations were not available. However, inferences can be made based on the values of θ_{fc} and total amount of rainfall received at each of these sites. Use of total amounts can lead to overpredictions because it is the "effective" rainfall (after correcting for evapotranspiration and runoff) that dictates the transport of N. Based on these considerations it is found that more leaching would occur at Lunyangwa (138 cm of rain per year), Lisasadzi (89 cm of rain per year) then Mbawa (81 cm of rain per year) although θ_{fc} values increase slightly in the opposite direction (Table 6-1).

The model simulations presented here are meant to be valid for well-drained homogeneous soil profiles where there is no runoff or preferential flow due to soil heterogeneity as is commonly the case with field soils. Since the Lilongwe series at Chitedze are considered to be well aggregated, it can be assumed that the assumption that all pore sequences participate in solute flow is only partially correct. The soil-water that resides inside small (micropores) pore domains of the aggregates probably do not participate in the solute flow process. Thus, it remains to determine the size of the water stable aggregates, the influence of runoff and the approprietness of the soil surface boundary conditions that do not take into account surface ponding. Another important consideration is nitrogen flush that occurs soon after the onset of the rains. Wood (1962) estimated that up to 60 μg N g^{-1} soil can be nitrified from organic matter at the beginning of the rainy season. These N content values were found to be less than 10 μg N g^{-1} soil by mid-January. These reduced N contents can be attributed to increased plant N uptake, leaching and denitrification in the presence of increased crop growth, increased soil water contents and reduced soil temperatures. Thus, split N applications applied in January should have beneficial effects on crop growth, early establishment and the final grain yields.

Nitrogen Uptake (1952/53, 1967/68 and 1973/74)

Nitrogen uptake data were considered for a corn crop that matured in 130 days with a maximum N uptake of 280 kg N ha^{-1}. The potential evapotranspiration data was extracted form the work of Pike and Remington (1965). The maximum rooting depth was taken as 120 cm, after the experiments of Wood (1962). The other input parameters are as described before.

Fig. 6-6a presents cumulative N uptake for 1952/53 and 1967/68 growing seasons. The resultant curves indicate that the assumed potential maximum N uptake of 280 kg N ha^{-1} was not achieved in both years. Other factors, other than water and nitrogen, restricted N uptake. The N uptake value for 1952/53 was 11% higher than for the

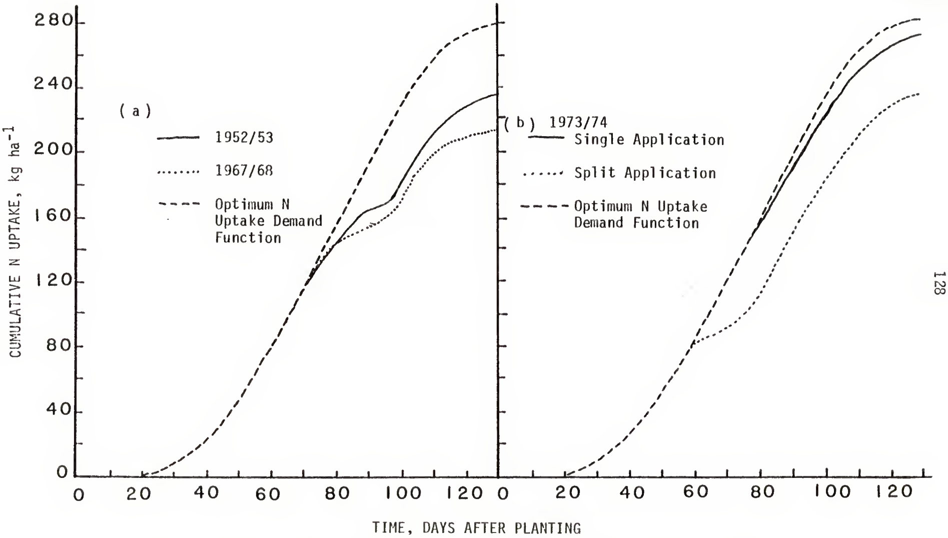


Fig. 6-6 Predicted Cumulative Plant N Uptake During the Growing Season, Chitedze

1967/68 growing season. This reduction in N uptake can be attributed to differences in rainfall distribution patterns for these years.

The 1973/74 growing season data (Fig. 6-6b) indicate that an N uptake of up to 270 kg N ha^{-1} was attained, representing only a 10 kg N ha^{-1} loss or still remaining in the soil profile. During this year both water and nitrogen did not limit corn growth. These values are 28% and 15% higher than those obtained for the 1967/68 and 1952/53 growing seasons, respectively.

However, since NITROSIM predicted that the maximum solute peak had advanced beyond the root zone before the end of the growing season, a split N application was tried. N was applied 1, 40 and 80 days after planting in three equal amounts that totalled 224 kg N ha^{-1}. Fig. 6-6b present the results for this simulation. The split application was 16% lower than the single application at harvest. Limiting soil-water conditions and limiting N conditions before the third application was applied, reduced the uptake rate 60 days after planting. When the third application was made 20 days later it did not attain the uptake of the single application. The root depth function used in these simulations indicate that N was within the root zone (Fig. 6-6c). The same was true for low and medium rainfall years (Fig. 6-6a,b). Above average rainfall data show that N had leached beyond the root zone during some parts of the growing season.

CHAPTER 7

SUMMARY AND CONCLUSIONS

Gainesville Study

Field Studies

All treatments were affected by periodic mid-day soil-water stressing conditions during the vegetative growth stages. W_1 and W_0 suffered from a two-week water stress imposed during the reproductive growth stage while W_2 had sufficient water stored in the profile that satisfied the crop's demand. This resulted in W_2 yielding significantly more grain yield than either W_0 or W_1. Grain yields in W_1 and W_0 were not statistically different. These results demonstrated that the duration and the timing of the soil-water stress conditions are important factors which determine the final grain yield.

Subsoiling did not influence the amount of water stored in the root zone, cumulative N uptake and the final grain yields under the present experimental conditions. This is because the subsoiling was ineffective (as indicated by penetrometer readings after planting) and because a more favorable (uniform) rainfall distribution pattern was experienced in 1983.

NO_3^--N moved vertically downwards in response to water input events, while NH_4^+-N was retarded in surface soil layers owing to the adsorption/desorption process. The concentrations of these N species were highly variable both in time and space. Non-uniform (banded) application of N fertilizer, minimal lateral spreading of N from the fertilizer band and the inability to collect soil samples on the band were identified as the reasons for the observed variability. The problem of N variability was partially resolved when integral amounts of N residing in the soil profile were considered. This proved to be a useful criterion for characterizing N under field conditions because of the large spatial domain over which total N masses were summed.

Based on these results, the following conclusions can be arrived at

(i) If the soil-water stored in the root zone is at or near the lower limit of availability during the reproductive growth stages up to 50% reductions in grain yields can occur.

(ii) If the soil-water stored in the root zone is near or at the lower limit of availability for short periods of time during the vegetative growth stages, minimal damaging effects are caused to significantly reduce the final grain yield despite reductions in N uptake and dry matter accumulations.

(iii) Although subsoiling did not significantly influence the amount of water stored in the root zone, cumulative N uptake or the final grain yields, it should still be incorporated in later experiments. This will facilitate deeper rooting resulting in increased water and nutrient extraction from deeper soil depths.

(iv) Future studies should pay particular attention to non-uniform N application and non-uniform soil surface boundary conditions. The sampling protocals and methods for data analysis and interpretation need to be resolved.

N uptake values were small early in the season, but increased in an exponential manner until silking time. Maximum N uptake values ranged between 40 and 80 kg N ha^{-1} for leaves, 20 and 60 kg N ha^{-1} for stems, and 20 and 40 kg N ha^{-1} for reproductive parts. After silking there was an efflux of N from all plant parts into the grain. At harvest the cumulative N uptake values ranged between 20 and 45 kg N ha^{-1} for leaves and were less than 15 kg N ha^{-1} in all other plant parts. N accumulation in the grain (range 130 to 194 kg N ha^{-1}) and the whole plant exhibited the expected sigmoid-shaped curve.

Low nitrogen treatments had higher nitrogen use efficiency (range 104 to 148%) when compared to high nitrogen treatments (range 56 to 64%). A possible luxury uptake of N or a greater utilization of N by underground plant parts were suggested as causes for these observed values. The other reason can be ascribed to other crop production variables that might equally have been important in determining grain yield. Plant sampling throughout the growing season (at shorter intervals than attempted in this study) is required to characterize N dynamics. Additional studies are required to better quantify grain yield as a function of cumulative N uptake or to identify those plant components whose cumulative N uptake values correlates best with the final grain yield.

Simulation Studies

The simulation model NITROSIM was able to track the advance of the solute peak locations fairly well. There were some instances when the model overpredicted the solute peak locations. This is an expected result because NITROSIM considers the convective flux term only. In this regard, NITROSIM is essentially equivalent to the Piston Displacement Model (PDM). Soil N content values were very variable. It was therefore difficult to compare measured NO_3^--N and NH_4^+-N concentration profiles with the simulated values. However, the integral amounts of N residing in the soil profile provided a useful method for describing nitrogen behavior under field conditions. Generally the model underpredicted the total nitrogen masses residing in the soil profile.

Measured and simulated plant N uptake values agreed reasonably well. Better agreement was observed for high N under optimum soil-water conditions than for low N or the reproductive water stress conditions.

Malawi Study

Field and Laboratory Studies

Soil-water characteristic data indicated that the soils studied have low water holding capacities. Field capacity values ranged from 0.11 to 0.36 $cm^3\ cm^{-3}$, while wilting point values varied from 0.03 to 0.22 $cm^3\ cm^{-3}$. Saturated hydraulic conductivity values ranged from 2 to 52 $cm\ hr^{-1}$ for soil surface (0-15 cm) layers, indicating that these soils are readily permeable to percolating water.

Chemical analysis data indicated that these soils have a wide range of pH values. Acid soils (having a pH of less than 5.5) are found at Lunyangwa, while neutral pH soils are found at Ngabu (Shire Valley). The pH values for soils collected from other sites are intermediate. Based upon the pH and zero points of charge (ZPC) values, it was concluded that all soils studied can be characterized as not having a predominance of variable surface charge clays, except for the Lunyangwa soils. Hence, retardation of nitrate leaching in these soils would be expected to be minimal.

Further characterization of Malawi soils should include adsorption/desorption isotherms for NH_4^+-N and other nutrient elements that are of agricultural importance. Data are also required on soil hydraulic properties for other soil series.

Simulation Studies

Simulation results indicated that during years of high rainfall, NO_3^--N would leach beyond the root zone (more than 120 cm). Split applications of N fertilizer reduced the leaching losses of N beyond the root zone. During years of low and medium rainfall the NO_3^--N pulse did not leach beyond the root zone. There was greater N uptake when soil-water was not limiting crop growth during years of high rainfall. Stressing soil-water conditions (during years of low and medium rainfall) resulted in reduced cumulative N uptake values.

These simulation results maybe useful in designing a nitrogen management experiment that takes into account (i) the corn N uptake demand function and (ii) N leaching patterns.

APPENDIX 1

SOIL INFORMATION -- MALAWI STUDY

Table A1-1 Profile description of the Lilongwe series, Block D, Chitedze*

Horizon	Depth -cm-	Profile Description
A_p	0-20	Dark reddish brown (5yr 3/2) moist, sandy clay loam, strong fine crumb structure; slightly sticky and plastic; very porous; abundant fine and medium roots; irregular boundary.
B_{t1}	20-38	Dark reddish brown (5yr 3/2) moist, sandy clay; moderate medium subangular blocky structure; sticky, plastic, friable to firm, hard; patchy, think cutans of clay with iron oxides; common, fine and micro, discontinuous, random interstitial and tabular open pores; few fine roots; clear wavy boundary.
B_{t2}	38-60	Dark red (2-5yr 3/6) moist, clay; moderate, medium, subangular block structure; sticky, plastic, firm, hard; broken, very thin clay cutans probably with iron oxides; common to many interstitial micro pores; few fine and very fine roots; clear smooth boundary.
B_3	60-120	Dark red (2-5yr 3/6) moist, clay; very weak coarse subangular blocky structure; sticky, plastic, friable, slightly hard; porous, few fine roots.

* After Lowole, M., 1982 (personal communication)

Table A1-2 Profile description of some Malawi Soil Series*

Soil Series	Location	Genetic group and some morphological characteristics
Mazamba	Lunyangwa	Ferrisol (Oxisol**) Topsoil is dark reddish brown. All horizons are easily friable; rapid permeability; weak block structure that breaks into weak fine crumbs.
Bulala	Bulala	Strongly ferallitc sandy latosol (Ultisol). Top soil is coarse sand or sandy loam. The structure is from single grain to weakly massive.
Loundon	Mbawa	Weakly ferallitic latosol (Alfisol). Top soil is sandy clay loam or sandy loam with a strongly developed shallow textural B horizon (argillic horizon) of sandy clay or clay. The structure is weak fine to medium blocky.
Kafukule	Ehehleni Turn Off	Strongly ferallitic latosol (Utisol). Top soil is brown or dark brown loamy coarse sand or coarse sandy loam with low organic matter content. The structure is single grained to weakly massive in all horizons.
Kasungu	Lisasadzi	Strongly ferallitic latosol with laterite (Ultisol). Top soil is dark greyish brown sandy loam or loamy sand. Subsoil is typically yellowish red or reddish brown. Iron concretions may start at 46 or 122 cm depth. The soil structure is weak blocky on the surface horizons to massive in the subsoil.
Lilongwe	Chitedze	Ferruginous latosol (Alfisol). The morphological characteristics are as described in Table A1-1b above.

Table A1-2...Continued

Soil Series	Location	Genetic group and some morphological characteristics
Mchinji	Mchinji	Weakly ferallatic latosol (Ultisol). Top soil has a sandy clay loam texture, with a profile that has a uniform appearance. The soil structure is moderate or weak with noticeable ped cutans in the lower horizons.
Salima	Salima	Alluvial calcimorphic soil (Inceptisol). Top and subsoil horizons are very dark brown to very dark greyish brown with some mottles indicating imperfect drainage characteristics. Most horizons are sandy clay loam or sandy loams. The structure is massive in sandy horizons, moderate, medium or coarse blockly in heavier horizons and strong blocky in clays.
Makande#	Ngabu	Semi arid - brown (Vertisol). Top soil is very dark brown or slightly blacker becoming paler with depth. The texture paler with depth. The texture is sandy clay loam including both coarse and fine sand, sandy loams, clay loams and clays. The soils are formed from drift derived from basic rocks; strongly structural, easily friable when dry and very sticky when wet.
Tomali#	Kasinthula	Semi-arid - brown (Alfisol). Top soil is very dark grey (moist). The texture is sandy clay loam and the structure is weak and medium blocky; and formed on imperfect drainage sites.
Mwanza##		(Alfisol)

* - After Young and Brown (1962) and Brown and Young (1965).

** - Approximate Soil Taxonomy soil orders were provided by E. Ntokotha (personal communication).

# This classification is given in the Annual Report of the Department of Agriculture for the year 1960/61 (Anonymous, 1962, Government Printer, Zomba, Malawi).

## No documented profile characteristics are available for the Mwanza soil.

APPENDIX 2

MEASURED FIELD DATA -- GAINESVILLE STUDY

Table A2-1 Measured profile soil-water in different treatment combinations during the growing season at IREP, Gainesville, Florida, 1983

Depth	Soil Sampling Dates										
	2/21	3/7	3/21	3/29	4/13	4/27	5/11	5/27	6/11	6/25	7/18
--cm--	cm										
	$W_1C_0N_0$										
0-15	1.3	1.2	1.1	1.3	1.2	0.8	1.6	0.2	0.9	1.4	0.7
15-30	1.3	1.4	1.2	1.3	1.4	1.2	1.5	0.5	1.0	1.4	0.9
30-45	1.3	1.4	0.9	1.4	1.3	1.0	1.5	0.8	1.2	1.5	1.0
45-60	1.3	1.3	0.9	1.3	1.3	1.2	1.2	0.9	1.3	1.4	1.0
60-75	1.2	1.2	0.8	1.2	1.2	1.0	1.2	0.9	1.1	1.7	1.1
75-90	1.1	1.3	0.7	1.2	1.3	1.0	1.2	0.9	1.1	1.6	1.0
90-105	1.3	1.2	0.8	1.1	1.4	1.2	1.0	0.9	1.2	1.5	1.0
	$W_1C_0N_1$										
0-15	1.4	1.2	0.9	1.3	1.2	0.8	1.5	0.2	0.9	1.4	0.8
15-30	1.5	1.4	1.1	1.4	1.1	1.2	1.3	0.3	1.0	1.5	1.0
30-45	1.4	1.3	1.1	1.3	1.3	1.1	1.3	0.4	1.2	1.6	1.0
45-60	1.2	1.3	1.0	1.2	1.3	1.1	1.3	1.0	1.2	1.7	1.0
60-75	1.2	1.3	0.9	1.1	1.2	1.1	1.2	0.6	1.2	1.5	1.0
75-90	1.1	1.3	0.9	1.2	1.2	1.0	1.0	0.7	1.3	1.3	1.1
90-105	1.1	1.3	0.9	1.1	1.2	1.1	1.0	0.7	1.2	1.0	0.8

Table A2-1..Continued

Depth	Soil Sampling Dates 2/21	3/7	3/21	3/29	4/13	4/27	5/11	5/27	6/11	6/25	7/18
--cm--					cm						
					$W_2C_1N_0$						
0-15	1.3	1.1	1.2	1.3	1.0	0.9	1.5	0.8	0.9	1.5	0.9
15-30	1.4	1.3	1.0	1.4	1.3	1.0	1.5	0.8	1.2	1.6	1.1
30-45	1.2	1.3	0.9	1.4	1.3	1.0	1.5	0.8	1.2	1.6	1.1
45-60	1.2	1.3	0.9	1.2	1.2	1.1	1.2	1.0	1.3	1.6	1.1
60-75	1.2	1.3	0.9	1.2	1.2	1.0	1.1	0.8	1.2	1.4	1.0
75-90	1.1	1.5	0.8	1.1	1.3	1.1	1.1	0.9	1.1	1.1	1.1
90-105	1.3	1.5	0.8	1.1	1.2	1.3	1.1	1.0	1.1	0.9	0.9
					$W_2C_1N_1$						
0-15	1.2	1.2	1.1	1.5	1.2	1.1	1.3	0.7	0.8	1.4	0.8
15-30	1.4	1.6	1.2	1.4	1.4	1.3	1.1	0.6	1.1	1.4	1.0
30-45	1.4	1.3	1.0	1.3	1.3	1.3	1.1	0.7	1.2	1.4	1.2
45-60	1.3	1.2	1.0	1.3	1.3	1.1	1.1	0.8	1.2	1.5	1.1
60-75	1.2	1.3	0.8	1.2	1.1	1.1	1.1	0.8	1.1	1.3	1.0
75-90	1.1	1.5	0.8	1.1	1.3	1.1	1.1	0.9	1.1	1.1	1.1
90-105	1.3	1.5	0.8	1.1	1.2	1.3	1.1	1.0	1.1	0.9	0.9

Table A2-1..Continued

Depth	Soil Sampling Dates										
	2/21	3/7	3/21	3/29	4/13	4/27	5/11	5/27	6/11	6/25	7/18
--cm--	cm										
	$W_2C_0N_0$										
0-15	1.3	1.3	1.1	1.4	1.3	0.8	1.5	0.9	1.0	1.5	0.8
15-30	1.6	1.3	1.2	1.4	1.4	1.2	1.5	0.9	1.3	1.8	1.1
30-45	1.4	1.5	1.0	1.3	1.5	1.0	1.3	0.8	1.2	1.6	1.1
45-60	1.2	1.2	1.1	1.2	1.3	0.9	1.1	0.9	1.3	1.6	1.0
60-75	1.2	1.2	0.9	1.2	1.2	1.1	1.1	1.1	1.2	1.8	1.0
75-90	1.3	1.4	0.9	1.1	1.4	1.2	1.2	1.0	1.2	1.4	0.9
90-105	1.4	1.3	0.9	1.1	1.3	1.2	1.1	0.9	1.2	1.3	1.0
	$W_2C_0N_1$										
0-15	1.2	1.2	1.1	1.2	1.2	0.9	1.6	0.9	0.8	1.4	0.7
15-30	1.4	1.3	1.1	1.4	1.1	1.1	1.4	0.8	1.1	1.4	1.0
30-45	1.2	1.3	1.0	1.4	1.3	1.0	1.3	0.7	1.1	1.4	1.0
45-60	1.1	1.3	1.0	1.3	1.2	1.2	1.3	0.8	1.1	1.5	0.9
60-75	1.1	1.3	0.9	1.3	1.3	1.1	1.2	0.9	1.1	1.5	1.1
75-90	1.0	1.3	1.0	1.2	1.3	1.1	1.1	1.1	1.1	1.6	0.9
90-105	1.1	1.4	0.9	1.1	1.2	1.0	1.1	1.0	1.2	1.12	0.9

Table A2-1...Continued

Depth	Soil Sampling Dates										
	2/21	3/7	3/21	3/29	4/13	4/27	5/11	5/27	6/11	6/25	7/18
--cm--	cm										
	$W_1C_1N_0$										
0-15	1.5	1.5	1.1	1.2	1.1	1.1	1.4	0.4	0.9	1.3	0.7
15-30	1.6	1.5	1.2	1.4	1.3	1.3	1.5	0.6	1.2	1.4	1.1
30-45	1.3	1.3	0.9	1.2	1.3	1.1	1.2	0.8	1.2	1.5	1.3
45-60	1.3	1.3	0.9	1.2	1.3	1.1	1.2	0.8	1.2	1.5	1.0
60-75	1.3	1.3	0.9	1.1	1.3	1.2	1.1	0.9	1.2	1.4	0.8
75-90	1.2	1.2	0.9	1.0	1.3	1.0	1.1	0.9	1.2	1.4	1.1
90-105	1.2	1.6	0.9	1.2	1.2	1.1	1.2	1.2	1.2	1.3	0.9
	$W_1C_1N_1$										
0-15	1.1	1.3	1.0	1.2	1.2	1.1	1.6	0.4	1.0	1.2	0.8
15-30	1.3	1.4	1.0	1.5	1.4	1.3	1.3	0.3	1.1	1.3	1.0
30-45	1.3	1.4	0.9	1.4	1.3	1.3	1.2	0.8	1.2	1.4	1.3
45-60	1.2	1.3	0.8	1.3	1.3	1.1	1.1	0.8	1.1	1.5	1.2
60-75	1.1	1.3	0.9	1.2	1.2	1.0	1.1	0.9	1.2	1.4	1.2
75-90	1.1	1.2	0.9	1.2	1.2	0.9	1.1	1.0	1.3	1.4	1.2
90-105	1.1	1.3	0.8	1.2	1.2	1.1	1.0	1.1	1.1	0.9	1.1

Table A2-2 Measured average soil NH_4^+-N in different treatment combinations during the growing season at IREP, Gainesville, Florida, 1983

Depth	Soil Sampling Dates										
	2/21	3/7	3/21	3/29	4/13	4/27	5/11	5/27	6/11	6/25	7/18
--cm--						cm					
						$W_1C_0N_0$					
0-15	6.8	10.4	18.3	10.5	5.9	20.7	7.1	32.9	8.6	5.3	9.6
15-30	4.7	33.0	16.5	9.3	2.4	3.5	18.9	4.7	4.7	3.0	7.1
30-45	6.9	24.0	12.0	7.1	3.5	2.4	26.4	5.6	3.0	3.0	4.7
45-60	5.9	15.2	10.5	7.1	2.4	2.4	7.12	2.4	2.4	2.4	4.7
60-75	4.7	11.7	17.4	3.5	2.4	2.4	7.1	3.8	2.4	3.0	7.1
75-90	4.7	11.7	9.3	4.7	2.4	2.4	2.4	3.0	2.4	2.4	2.4
90-105	3.5	9.3	12.8	4.7	2.3	2.3	2.3	3.0	3.0	2.3	9.7
						$W_1C_0N_1$					
0-15	6.8	9.2	8.1	27.6	3.5	60.8	15.5	328.8	88.8	26.0	14.9
15-30	4.7	20.0	15.3	14.1	2.4	26.0	7.1	20.6	49.5	12.5	9.6
30-45	6.9	10.4	8.1	7.1	2.4	22.8	15.2	6.5	19.2	12.5	9.6
45-60	5.9	4.7	7.1	4.7	2.4	26.7	4.7	4.7	10.5	3.0	7.1
60-75	4.7	7.1	10.5	2.4	2.4	26.7	3.0	2.4	6.45	3.0	3.5
75-90	4.7	14.0	12.8	4.7	2.4	24.5	3.8	2.4	3.0	2.4	4.7
90-105	3.5	5.9	10.5	3.5	2.3	12.8	3.0	2.3	2.3	4.7	3.5

Table A2-2...Continued

Depth	Soil Sampling Dates										
	2/21	3/7	3/21	3/29	4/13	4/27	5/11	5/27	6/11	6/25	7/18
--cm--	cm										
						$W_2C_1N_0$					
0-15	6.8	4.7	17.4	12.8	9.3	36.8		29.9	17.7	13.8	27.6
15-30	4.7	8.1	12.0	9.3	2.4	16.5		20.6	6.4	4.7	18.2
30-45	6.9	5.9	14.4	10.5	2.4	7.1		11.3	3.0	2.4	16.1
45-60	5.9	3.5	7.1	58.5	2.4	2.4		3.0	2.4	2.4	16.1
60-75	4.7	7.1	12.0	2.4	2.4	2.4		2.4	3.0	2.4	11.7
75-90	4.7	2.4	7.1	2.4	2.4	2.4		2.5	2.4	5.3	14.0
90-105	3.5	2.3	3.5	2.3	2.4	2.3		3.0	2.3	3.0	16.2
						$W_2C_1N_1$					
0-15	6.8	4.7	13.8	5.9	3.5	48.2	20.7	271.5	20.0	13.1	17.3
15-30	4.7	9.3	12.0	24.8	4.7	14.2	10.2	5.6	4.7	4.7	10.5
30-45	6.9	13.2	4.7	5.9	3.5	4.7	4.7	3.0	3.9	8.7	21.6
45-60	5.9	11.7	13.8	3.5	2.4	2.4	2.5	2.4	2.4	2.4	18.6
60-75	4.7	13.2	5.9	2.4	4.7	2.4	2.5	2.4	2.4	4.7	24.5
75-90	3.5	9.3	2.4	5.9	2.4	3.0	3.0	2.4	2.4	9.6	1.1
90-105	3.4	2.3	12.8	2.3	2.3	2.3	2.5	3.8	3.0	2.3	12.8

Table A2-2...Continued

Depth	Soil Sampling Dates										
	2/21	3/7	3/21	3/29	4/13	4/27	5/11	5/27	6/11	6/25	7/18
--cm--	cm										
						$W_2C_0N_0$					
0-15	6.8	4.7	12.0	5.9	7.1	3.5	7.1	27.6	13.1	20.7	10.6
15-30	4.7	5.9	41.3	15.2	4.7	4.7	3.5	17.3	5.6	5.3	7.1
30-45	6.9	5.9	15.6	8.1	3.5	2.4	2.4	14.3	3.9	5.3	4.7
45-60	5.9	5.9	19.8	5.9	3.5	2.4	2.4	6.5	3.0	3.0	4.7
60-75	4.7	4.7	15.2	2.4	3.5	4.7	2.4	3.9	2.4	2.4	12.8
75-90	4.7	10.4	16.5	2.4	4.7	2.4	2.4	3.0	2.4	2.4	12.8
90-105	3.4	5.9	5.9	2.3	2.3	2.3	3.5	2.3	3.0	2.3	4.7
						$W_2C_0N_1$					
0-15	6.8	3.5	19.8	10.5	12.0	102.2	35.1	273.2	51.2	18.3	4.0
15-30	4.7	8.1	31.8	8.1	12.0	83.6	8.9	9.5	36.0	7.1	9.6
30-45	6.9	8.1	30.0	5.9	5.9	33.6	23.3	5.6	8.0	7.1	8.4
45-60	5.9	5.9	7.1	3.5	3.5	30.3	24.9	6.5	3.9	3.9	7.1
60-75	4.7	8.1	12.8	2.4	9.3	33.6	15.6	3.0	3.0	2.4	7.1
75-90	4.7	2.4	5.9	2.4	2.4	21.0	10.1	2.4	2.4	2.4	4.7
90-105	3.4	2.3	12.0	2.3	10.5	18.5	2.3	6.9	2.3	3.0	2.3

Table A2-2...Continued

Depth	Soil Sampling Dates										
	2/21	3/7	3/21	3/29	4/13	4/27	5/11	5/27	6/11	6/25	7/18
--cm--	----------					cm					----------
						$W_1C_0N_0$					
0-15	6.8	4.7	10.5	4.7	2.4	3.5	-	13.1	11.6	23.0	10.8
15-30	4.7	13.2	9.3	12.0	4.7	2.4	-	9.5	5.6	8.7	10.8
30-45	6.9	8.1	8.1	12.0	5.9	2.4	-	7.8	3.0	4.7	5.9
45-60	5.9	10.4	8.1	8.2	2.4	2.4	-	3.0	4.7	2.4	4.7
60-75	4.7	7.1	9.3	4.7	2.4	2.4	-	2.4	3.0	2.4	5.9
75-90	4.7	7.1	10.5	2.4	2.4	2.4	-	6.5	2.4	2.4	4.7
90-105	3.5	3.5	7.1	2.3	2.3	2.3	-	2.3	2.3	2.3	5.9
						$W_1C_0N_1$					
0-15	6.8	8.8	19.8	8.1	7.1	80.4	15.3	343.5	53.4	14.4	14.4
15-30	4.6	18.0	15.1	7.1	2.4	28.2	8.7	7.8	24.8	6.5	9.6
30-45	6.9	19.2	23.3	12.0	7.1	15.6	3.9	6.5	20.0	9.6	8.9
45-60	5.9	9.3	7.1	9.3	2.4	8.1	2.4	3.0	10.1	9.6	7.1
60-75	4.7	7.1	12.8	3.5	2.4	7.1	3.0	2.4	3.9	6.5	7.1
75-90	4.7	4.7	12.8	2.4	2.4	7.1	3.8	2.4	2.4	2.4	4.7
90-105	3.5	9.3	4.7	2.3	2.3	9.3	2.3	2.3	5.3	2.3	6.2

Table A2-3 Measured average soil NO_3^--N in different treatment combinations during the growing season at IREP, Gainesville, Florida, 1983

	Soil Sampling Dates										
Depth	2/11	3/07	3/21	3/29	4/13	4/27	5/11	5/25	6/11	6/25	7/18
-cm-	kg ha^{-1} (15 cm soil depth)$^{-1}$										
	$W_1C_0N_0$										
0-15	17.3	8.1	291.3	104.4	3.5	24.2	2.5	4.7	5.3	4.7	11.5
15-30	20.1	2.4	16.5	68.3	2.4	3.5	4.7	3.0	3.0	3.9	4.7
30-45	4.5	2.4	6.0	9.6	7.2	2.4	7.2	2.4	2.4	4.7	7.2
45-60	3.5	2.4	7.1	4.7	15.2	2.4	4.7	2.4	2.4	2.4	2.4
60-75	2.4	11.7	10.5	3.5	15.2	2.4	2.4	3.0	2.4	4.7	2.4
75-90	2.3	2.4	9.3	3.5	7.8	2.4	2.4	8.5	2.4	3.0	2.4
90-105	2.3	2.3	4.7	3.5	3.5	2.3	2.3	7.2	2.3	2.5	4.7
	$W_1C_0N_1$										
0-15	17.3	5.7	969.6	54.0	2.4	27.6	9.2	330.0	40.7	2.9	9.2
15-30	20.1	2.4	10.7	83.5	2.4	5.9	6.5	9.2	34.7	16.5	7.2
30-45	4.5	2.4	7.1	6.0	2.4	2.4	15.2	3.0	46.4	26.4	6.0
45-60	3.5	2.4	10.5	2.4	14.0	2.4	8.6	5.2	31.8	16.4	3.5
60-75	2.4	2.4	14.0	2.4	10.5	2.4	4.7	2.4	8.6	10.1	6.0
75-90	2.3	2.4	11.7	2.4	3.5	27.6	2.4	2.4	4.7	5.3	4.7
90-105	2.3	2.3	8.4	2.3	2.3	52.5	6.3	2.3	3.0	3.9	13.8

Table A2-3....Continued

	Soil Sampling Dates										
Depth	2/11	3/07	3/21	3/29	4/13	4/27	5/11	5/25	6/11	6/25	7/18
-cm-	kg ha^{-1} (15 cm soil depth)$^{-1}$										
						$W_2C_1N_0$					
0-15	17.3	2.4	655.2	29.9	2.4	12.6		10.8	3.0	5.3	9.9
15-30	20.1	2.4	11.9	27.2	4.7	4.7		5.2	2.4	3.0	6.3
30-45	4.5	2.4	10.8	7.2	8.4	2.4		2.4	2.4	3.0	4.7
45-60	3.5	2.4	5.9	3.5	12.8	2.4		2.4	2.4	2.4	3.9
60-75	2.4	2.4	5.9	2.4	25.7	2.4		2.4	2.4	2.4	5.3
75-90	2.3	2.4	5.9	2.4	12.8	2.4		2.4	2.4	2.4	3.0
90-105	2.3	2.3	5.9	2.4	4.7	2.3		5.3	2.3	2.3	2.3
						$W_2C_1N_1$					
0-15	17.3		488.9	39.0	2.4	20.7	9.2	256.4	8.5	4.7	3.5
15-30	20.1		10.7	28.2	2.4	3.5	19.5	7.2	3.9	3.0	4.7
30-45	4.5		8.4	7.2	2.4	3.5	19.2	3.0	2.4	3.0	3.5
45-60	3.5		4.7	3.5	4.7	2.4	13.2	2.4	2.4	2.4	4.7
60-75	2.4		9.3	2.4	5.9	2.4	3.0	2.4	2.4	3.9	2.4
75-90	2.3		4.7	2.4	4.7	2.4	3.9	2.4	2.4	3.0	2.4
90-105	2.3		4.7	2.2	2.3	33.5	13.2	2.3	2.3	2.3	2.3

Table A2-3...Continued

Depth	2/11	3/07	3/21	3/29	4/13	4/27	5/11	5/25	6/11	6/25	7/18
-cm-	kg ha^{-1} (15 cm soil depth)$^{-1}$										
							$W_2C_0N_0$				
0-15	17.3	2.4	587.6	65.4	10.4	10.4	2.4	4.7	4.7	4.7	6.0
15-30	20.1	2.4	10.7	41.3	5.9	2.4	2.4	7.8	4.7	3.0	4.6
30-45	4.5	2.4	6.0	4.8	48.0	2.4	2.4	13.7	2.4	30.0	6.0
45-60	3.5	2.4	6.7	2.4	29.1	2.4	2.4	10.1	3.9	2.4	4.7
60-75	2.4	2.4	8.1	2.4	48.0	2.4	2.4	7.2	3.0	3.0	3.5
75-90	2.3	2.4	9.3	2.4	35.0	2.4	2.4	21.6	2.4	2.4	3.5
90-105	2.3	2.3	8.1	2.4	6.7	5.9	2.4	15.5	2.3	2.3	3.5
							$W_2C_0N_1$				
0-15	17.3	2.4	367.2	94.1	4.7	20.7	10.8	247.2	6.9	5.3	11.6
15-30	20.1	2.4	11.9	56.6	3.5	7.2	16.5	11.9	14.1	14.1	10.7
30-45	4.5	2.4	14.4	9.6	7.2	4.7	26.5	5.6	5.6	14.1	7.2
45-60	3.5	2.4	5.9	3.5	11.7	2.4	9.2	3.9	3.9	9.3	3.5
60-75	2.4	2.4	15.2	2.4	25.7	4.7	9.2	4.7	2.4	14.7	3.5
75-90	2.3	2.4	15.2	2.4	16.4	11.7	41.1	3.9	2.4	15.6	4.7
90-105	2.3	2.3	5.9	2.3	2.3	38.1	50.1	9.9	2.3	17.8	6.0

Table A2-3...Continued

Depth	2/11	3/07	3/21	3/29	4/13	4/27	5/11	5/25	6/11	6/25	7/18
-cm-	---------------- kg ha^{-1} (15 cm soil depth)$^{-1}$ ----------------										
							$W_1C_1N_0$				
0-15	17.3	2.4	268.5	60.8	3.5	12.6		3.9	2.4	3.9	4.7
15-30	20.1	3.6	10.6	42.5	2.4	3.5		3.9	2.4	5.3	7.2
30-45	4.5	2.4	20.4	7.2	2.4	2.4		15.2	2.4	16.4	3.5
45-60	3.5	2.4	14.0	2.4	3.5	2.4		22.5	2.4	4.7	3.5
60-75	2.4	2.4	16.4	2.4	9.3	2.4		17.9	2.4	3.9	3.5
75-90	2.3	2.4	17.4	2.4	14.0	2.4		14.7	2.4	2.4	6.0
90-105	2.3	2.3	18.5	2.3	5.9	2.3		6.9	2.3	6.2	3.5
							$W_1C_1N_1$				
0-15	17.3	8.1	434.9	51.6	2.4	17.3	7.5	279.3	5.3	5.3	8.6
15-30	20.1	15.3	9.5	54.2	2.4	7.2	9.2	7.8	3.0	4.7	4.7
30-45	4.5	2.4	14.4	10.8	2.4	2.4	5.6	3.9	3.0	4.7	5.3
45-60	3.5	3.5	9.3	3.5	10.4	2.4	3.0	2.4	2.4	2.4	4.7
60-75	2.4	2.4	22.1	2.4	15.2	2.4	2.4	2.4	2.4	4.7	3.9
75-90	2.3	9.3	16.4	2.4	23.3	2.4	3.0	2.4	2.4	2.4	5.3
90-105	2.3	2.3	19.7	2.3	5.9	10.4	5.3	2.3	2.3	2.3	9.2

Table A2-4 Average dry matter yield in different plant components at IREP, Gainesville, Florida, 1983

		Soil Sampling Dates				
Treatment	Plant Part	5/10	5/23	6/11	6/27	7/18
		$MT\ ha^{-1}$				
$W_1C_0N_0$	Leaves (L)	0.6	1.7	1.5	1.5	1.6
	Stems (S)	0.5	2.5	2.3	1.6	1.2
	Reproductive Parts (R)	-	0.2	1.6	2.2	2.7
	Grain (G)	-	-	0.2	4.9	9.0
$W_1C_0N_1$	L	1.0	2.2	2.0	2.3	2.7
	S	1.2	3.4	3.8	1.5	2.1
	R	-	5.7	2.7	3.3	3.5
	G	-	3.7	2.9	5.2	3.3
$W_2C_1N_0$	L	0.8	1.4	1.8	1.3	1.6
	S	0.6	2.3	3.6	1.5	2.0
	R	-	3.7	2.9	5.2	3.3
	G	-	0.8	3.6	3.5	4.0
$W_2C_1N_1$	L	1.1	1.8	2.2	2.4	2.2
	S	1.4	3.7	3.3	2.6	2.5
	R	-	0.8	3.6	3.5	4.0
	G	-	-	2.2	7.8	12.8
$W_2C_0N_0$	L	1.3	1.3	1.3	1.7	1.9
	S	0.9	2.1	2.4	1.6	2.1
	R	-	0.4	2.0	2.6	4.1
	G	-	-	1.1	5.9	12.2
$W_2C_0N_1$	L	1.3	1.0	2.2	2.8	2.9
	S	1.5	4.2	4.0	2.3	2.4
	R	-	0.6	3.2	3.0	3.9
	G	-	-	2.2	6.0	10.0
$W_1C_1N_0$	L	0.8	1.3	1.5	1.9	1.6
	S	0.6	2.1	2.7	1.6	2.4
	R	-	0.2	1.6	2.1	2.9
	G	-	-	0.3	5.3	11.0
$W_1C_1N_1$	L	0.9	1.8	2.4	2.5	2.1
	S	1.3	4.0	4.8	2.4	3.4
	R	-	0.9	3.1	1.8	3.2
	G	-	-	1.6	7.1	11.6

Table A2-5 Cumulative nitrogen uptake in above ground plant components at IREP, Gainesville, Florida, 1983

Plant Part	Date	$W_1C_0N_0$	$W_1C_0N_1$	$W_1C_1N_0$	$W_1C_1N_1$	$W_2C_0N_0$	$W_2C_0N_1$	$W_2C_1N_0$	$W_2C_1N_1$
		Treatments							
		kg ha^{-1}							
Leaves	5/10	13.1	41.2	15.7	40.2	24.9	50.5	16.5	43.5
	5/23	38.4	78.5	32.3	56.3	34.0	35.1	38.2	61.1
	6/11	36.7	54.4	33.1	61.6	70.0	47.6	65.8	
	7/18	21.7	44.3	24.7	39.0	25.6	47.7	19.3	32.0
Stems	5/10	7.7	31.4	9.0	38.3	11.3	40.6	8.0	36.2
	5/23	24.0	39.8	20.9	55.1	20.4	56.5	21.5	42.9
	6/11	18.2	36.6	22.9	39.6	14.3	39.2	30.0	24.1
	7/18	13.0	15.4	15.2	20.5	10.4	18.3	12.2	15.1
Reproductive Parts	5/23	4.6	13.7	5.1	21.7	8.5	15.1	7.6	17.6
	6/11	27.5	33.4	23.6	36.5	27.7	40.0	35.4	40.0
	6/25	19.9	33.2	18.3	33.0	28.4	28.5	25.3	30.8
	7/18	15.5	16.9	18.2	19.6	24.1	13.5	20.3	24.1
Grain	6/11	7.2	44.6	9.2	44.7	30.3	52.0	28.8	46.9
	6/27	81.0	105.0	62.3	112.6	107.5	107.5	92.8	117.3
	7/28	126.0	176.6	149.5	186.6	187.7	152.4	129.8	193.9

Table A2-6 Grain yield data*

Treatment	Rep.	Yield	Treatment	Rep.	Yield
		- kg ha^{-1} -			- kg ha^{-1} -
$W_0C_0N_0$	1	4908	$W_1C_1N_0$	1	3809
	2	6060		2	6724
	3	3568		3	6309
	4	8498		4	7974
$W_0C_0N_1$	1	5707	$W_1C_1N_1$	1	7710
	2	5617		2	6984
	3	5547		3	7958
	4	7813		4	4722
$W_0C_1N_0$	1	5857	$W_2C_0N_0$	1	6205
	2	5585		2	7156
	3	3977		3	6672
	4	7414		4	7416
$W_0C_1N_1$	1	8094	$W_2C_0N_1$	1	12907
	2	5963		2	10950
	3	6078		3	11476
	4	3548		4	11628
$W_1C_0N_0$	1	5750	$W_2C_1N_0$	1	8833
	2	6673		2	9020
	3	3956		3	8286
	4	5569		4	7770
$W_1C_0N_1$	1	7020	$W_2C_1N_1$	1	11716
	2	10572		2	11171
	3	7113		3	10665
	4	7746		4	12784

* - Data provided by Dr. J. M. Bennett, Agronomy Department, University of Florida.

APPENDIX 3

INPUT DATA AND PARAMETERS FOR THE NITROSIM MODEL

Table A3-1 Data sets and input parameters for NITROSIM*

Data Set	Value of the Parameter
1	27/ 144/ 1/ 1/ 56/ 0.2;
2	4/ 2.5/ 4.5/ 10.0/ 0.0/ 10.0/ 0;
3	150/ 0.343/ 0.0042/ 0.0000163/ 0.00033 0.00005/ 0.0001;
4**	
5***	
6	0;
7	3; 10/ 0.03/ 30/ 0.02/ 60/ 0.03;
8	3; 10/ 0.077/ 30/ 0.06/ 60/ 0.095;
9	3; 10/ 0.14/ 30/ 0.11/ 60/ 0.13;
10	2; 0.0/ 0.2/ 60/ 0.25;
11	1; 50/ 0.20;
12	8; 0.0/ 1.53/ 15.0/ 1.53/ 30.0/ 1.57/ 45.0/ 1.60/ 60.0/ 1.55/ 75.0/ 1.55/ 90.0/ 1.55/ 120.0/ 1.54;
13	4; 15.0/ 12.0/ 45.0/ 7.0/ 75.0/ 6.0/ 105.0/ 6.0;
14	4; 15.0/ 17.0/ 45.0/ 15.0/ 75.0/ 5.0/ 105.0/ 1.0/;
15	2; 0.0/ 1500/ 60/ 9000
16	0.5/ 0.5/ 0.5/ 0.5/ 0.003

* Data sets and parameter values are documented by Rao et al. (1981)

** Rainfed - 51 water input events
Reproductive Stress - 58 water input events
Optimum Water - 60 water input events
Day 1 is the day when planting ended - 2/25/83
Day 144 is the day when corn was harvested - 7/18/83
Rainfall and irrigation events are given in Table 3-2 for each water management treatment.

*** N_0 4;
25/ 190.0/190.0/ 49/ 146.0/ 146.0/ 77/ 298.0/
298.0/ 98/ 213.0/213;

N_1 5;
25/ 190.0/ 190.0/ 49/ 405.0/ 405.0/ 56/
556.0/ 556.0/ 63/ 337.0/ 337.0/ 84/ 578/ 578;

APPENDIX 4

MONTHLY RAINFALL DATA -- MALAWI STUDY

Table A4-1 Rainfall distribution during the growing season (November to April), Chitedze, Lilongwe, Malawi; 1952/53, 1967/68, 1973/74

Date	Nov.			Dec.			Jan.			Feb.			Mar.			Apr.		
	1*	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
										cm								
1									0.3	1.8		0.1			0.1			0.2
2		2.5			1.0				0.5	1.8	1.3	0.1						2.2
3										0.1		0.1	3.6		2.2			0.2
4			3.5		0.1				1.1	0.1	0.1	0.1	3.0	0.1				1.4
5					0.1				0.1	0.2	0.1	1.8	1.5		0.1		0.2	0.1
6		0.5					1.3		0.1		0.3	1.5			0.2	0.5		0.1
7	0.7			4.3		0.2	1.7	1.1	0.3	0.36	0.1	0.1		2.1	1.5			
8	7.1				0.8		0.6		3.5		1.7	1.8		0.9	1.8			
9	1.0				1.9		5.6		0.6			0.6		2.0	1.0		0.1	0.1
10	1.1	0.1				0.4	0.4	6.4	2.6	0.2	0.9	0.2		0.2	2.0		3.3	0.5
11	0.1			1.3	0.6		3.6		0.1			0.6	1.0	0.9			0.6	

Table A4-1...Continued

Date	Nov.			Dec.			Jan.			Feb.			Mar.			Apr.		
	1*	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
										cm								
12							0.6	1.3	0.9		0.3		0.3	0.1	0.6			
13							0.8	0.1					1.5	0.7	0.4			
14	0.1						0.8	2.5	1.2			0.1	0.1		0.1			
15				0.5		3.6	1.1	0.4		0.3	0.9	3.9						
16				0.5		0.1		0.1	0.4		0.1		0.4					
17					0.5				1.9			4.0			4.4			
18				7.7	0.1	3.3	1.5	0.4	0.4	1.5	1.1	1.1			1.1		0.2	
19				0.3		2.3	0.2	0.3	0.8	1.4	0.2	2.0			2.0			
20				1.4				0.5	0.1					0.1				
21		3.2		0.4		0.9		2.6	1.5		0.2	0.9			0.9	0.7		
22					0.1	0.9	0.1	0.2	4.7	1.0		0.5			0.5			

Table A4-1...Continued

Date	Nov.			Dec.			Jan.			Feb.			Mar.			Apr.		
	1*	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
	cm																	
23				0.9	0.9	0.1		0.2	3.0			0.1	1.1		0.1			
24			0.8	0.3	6.5	0.3	0.2	0.3	0.1			0.8			0.8			
25		0.5		0.1		0.1		0.1	1.6		0.1	0.2			0.2			
26		0.1		4.7	2.1		1.9	3.1	0.2					0.2				
27					0.7	0.6		1.0			0.2							
28	0.2		0.2			0.1						1.1						
29				0.8		0.8		0.1	0.5			0.8						
30	1.2					5.1	0.4		0.6				0.1					
31							2.0		2.3									
Totals	11.4	6.5	5.0	17.5	15.4	19.0	22.8	20.7	29.4	9.0	7.6	22.5	12.6	7.3	21.1	1.2	4.4	4.8

* - 1 - 1952/53 2 - 1967/68 3 - 1973/74

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Alex Reuben Phyera Saka was born in Mzimba, Malawi, at Nkholobondo Village on October 31, 1950. The name Phyera means "the one who was born after twins which passed away." He attended Nkholobondo and Chimtembo Village Schools before proceeding the Hoho Full Primary School. After attending Kongwe Secondary School, he entered the University of Malawi (Chancellor College) where he received his BSc in 1974.

In the same year he was employed by the Ministry of Agriculture and Natural Resources under the Research Department. After working for two years, he entered the University of Newcastle Upon Tyme, England, where he received an MSc degree in soil science in 1978. After working for two years, he entered the University of Florida in January 1981 to persue graduate studies in soil physics. Upon his graduation he hopes to conduct some research on soil-water and nutrient transport in Malawian agricultural soils.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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